LONG-TERM OBSERVATIONS OF THREE MASSIVE X-RAY BINARY TRANSIENTS: 4U0115+63, V0332+53, AND GX301-2

By

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The known massive X-ray binaries, 4U0115+63, V0332+53, and GX301−2, which are considered to be "transients" or "highly variable," are looked at with the Vela 5B X-ray data. In order to exploit the full richness of the data, a reorganization of the data base was necessary with two main objectives: 1.) convert from time to celestial-coordinate order and 2.) transfer the data base to reside and run on a VAX. Upon completion of this effort, access to each 1-second observation for a given X-ray source for the 10 years spanned by the data could be accomplished quickly and easily, allowing a detailed study of the long-term time histories as well as short-term variations. The known periodicities in the sources are monitored for changes either in period or pulse shape. Also, new periods are searched for in the context of recent theoretical predictions. Combining the results obtained from these analyses, better models and perhaps a deeper understanding of the overall behavior of these systems can be achieved.

The sources chosen here are all B or Be/neutron star binaries. However, it is seen that they exhibit diverse temporal and spectral behaviors. Four previously unknown recurrences for 4U0115+63 are reported. Also now available to analysis are the pulse periods of the sources (ranging from 3 to 700 seconds) and a well-resolved monitor of the 41.5 day orbital period light curve for GX301−2. This source is the only one of this study which exhibits persistent periodic outbursts associated with periastron passage. A reanalysis of the 1973 outburst of V0332+53 on 1-second timescales reveals new information concerning the orbital and pulse periods of this unusual system as well as further details on the variability observed over timescales of seconds to hours.

CHAPTER I
INTRODUCTION

The advancement of scientific thought has not always come from systematic experimentation. It is, generally, the result of questions posed from the values, attitudes, and preconceptions shared by society at large. No amount of observation can produce a change in accepted scientific theory without a corresponding change in the social matrix. This has been true throughout history (recall Aristotle, Copernicus, Galileo, Ptolemy, Brahe, and Kepler) and, while in present time technological development and observational evidence has much greater weight in the accepted cosmology, vestiges of the old principles remain. Once a concept or classification becomes accepted, change is a long, slow process which is usually brought to completion by something more socially related than mounting observational contradiction.

Observations have continued to be made over the centuries, however, with ever improving techniques. The use of the optical telescope opened the first systematic pathway to observing the universe. With only a few exceptions, such as supernovae, the objects seen appeared to be relatively unchanging. This is, of course, a consequence of the stability of the nuclear processes underlying stellar energy production. As technology improved the sensitivity of the observations, small variations on timescales of order of days were seen in the stars.

These changes were due to either some "external" cause such as an eclipse or intervening dust cloud or to some "internal" variation such as a flare or the expansion/contraction of the stellar envelope.

The second observational window was opened after World War II with the advent of radio astronomy. The discovery of pulsars and their interpretation in terms of rapidly rotating condensed objects, such as neutron stars, was experimental proof of the theoretically predicted endpoint in the lives of some stars. However, regardless of the loosening of ideas about celestial perfection between the 16th and the mid-20th century, no one expected what was found on a rocket flight 18 June 1962. Searching for lunar X-ray emission, the experiment of Giacconi, Gursky, Paolini, and Rossi (Giacconi and Gursky 1974) found instead what eventually proved to be Scorpius X-1. Inspired by this unexpected find, which most doubted and sought to disprove, many more observations followed. The results led to a dynamic, powerful view of the universe.

Just as in the times of Copernicus and Galileo, change of a concept, once established, is still difficult for both society and science today. This is especially true for a field in which rapid technological advancement continually produces observational evidence which questions every previous observationally defined concept. X-ray astronomy finds itself in this position. Rather than abandoning a classification of a certain type of X-ray emitting system (such as the transients) because improving observations have shown the original definition to no longer hold true, complex modifications (through the use of adjectives) have been forced onto the term. There is, in fact, no observational difference between "transients," "recurrent transients," "classical transients," "transient-like variables," and "highly variable sources" if the observer looks at the X-ray sky long enough and with great enough sensitivity. Only a true difference in the physical processes which power the various outbursts of the various sources should justify the various classifications. The following work will investigate this possibility.

X-Ray Binaries

Data from the Uhuru satellite resulted in the association of several X-ray sources with mass exchange occurring between a normal star and a compact secondary (either a neutron star or black hole) in a bound system (Jones et al. 1974). Theoreticians had long before shown that infalling material onto such an object would be an efficient X-ray production mechanism (Shklovski 1967; Zel'dovich and Guseinov 1965; Salpeter 1973; Hayakawa and Matsuoka 1964). The equation relating mass exchange rates for a neutron star or black hole to the resulting X-ray luminosity is

$$\dot{M} \sim 10^{-9} L_{37} M_{\odot} \quad yr^{-1}$$

where $L_{37} = L/10^{37}\,\mathrm{ergs\,sec^{-1}}$. Such rates are not attainable from interstellar matter accretion, but they are observed to occur in various binary systems at certain stages of evolution.

Mass exchange can occur by three modes (for a basic description of the physics see Shapiro and Teukolsky 1973):

1.) Roche-lobe overflow of the primary.

2.) Enhanced stellar wind from the primary.

3.) Capture of circumstellar material from a Be star primary.

In the case of Roche-lobe overflow, the angular momentum of the accreting material will tend to form a differentially rotating disk around the secondary (Prendergast and Burbidge 1968). An approximately spherical stellar wind will produce a much smaller disk around the secondary, if it produces one at all. If the secondary is magnetized, as is thought to be the case for neutron stars, the infalling material will be channeled along the magnetic field lines toward the poles and create impact 'hot spots' on the neutron star surface. Pulsations in the X-ray flux, at the rotational period, will result if this pole is misaligned with the rotation axis.

A number of X-ray binaries are known to consist of an O or B star primary emitting a stellar wind driven by the primary's radiation pressure, orbited by a neutron star or black hole which captures a fraction of this wind and converts the potential energy of the accreted plasma into X-rays. While qualitatively feasible, X-ray production by accretion from an undisturbed spherical wind can fall several orders of magnitude below the observed luminosity in the case of some binary systems (e.g. SMC X-1 and Cen X-3). Modifications to the basic theory brought the observations closer to prediction—for example, the inclusion of the potential disturbance created by the presence of the secondary in the primary's gravitational field introduced an angle dependence into the mass-loss rates by the primary. Recently, Ho and Arons (1987) modeled the effect of the X-ray emission by the secondary on the radiation-driven wind of the primary. The results brought the observed luminosities of the SMC X-1 and Cen X-3 into good agreement with theoretical prediction.

In a Be star/neutron star binary, the behavior of the Be star controls the X-ray characteristics of the system (Rappaport and van den Heuvel 1982; Corbet 1984). A Be star is a B star which rotates so rapidly that an instability results via which material streams out from the equatorial plane and an expanding atmosphere is formed. This introduces strong emission lines of hydrogen and neutral helium into the stellar spectrum. Furthermore, these stars are known to throw off large amounts of matter from their equatorial regions at apparently random intervals. The capture and accretion of this material by the secondary is known to be the source of many of the observed X-ray transients. Recently, Penrod (1986,1987) has suggested that non-radial pulsation modes in the Be star can account for optical observations of bumps and wiggles in the spectral line shapes of several stars in this class and, possibly, be a driving mechanism for the observed mass ejections.

Pulsars

Much of the information available concerning X-ray binaries has come from the study of X-ray pulsars. There are more than 20 known pulsars (Rappaport and Joss 1983), with the pulse behavior generated by the magnetic channeling described in the previous section. The general trend in pulsars is a secular decrease in period, although short term spin downs are observed. The accepted theory of this behavior is as an effect of torques on the neutron star by the accreted matter. The equation, so far consistent with observation, for the rate of change in pulse period is (Rappaport 1982):

$$\dot{\mathrm{P}}/\mathrm{P} \sim -3 \times 10^{-5} \left(\frac{\zeta \mathrm{v_r}}{\mathrm{v_{ff}}}\right)^{1/7} \mathrm{M_x^{-10/7} R_6^{6/7} R_{g6}^{-2}} \mu_{30}^{2/7} \mathrm{L_{37}^{6/7} P} \quad \mathrm{yr}^{-1}$$

where the units for $\mathrm{M_x}, \mathrm{R_6}, \mathrm{R_{g6}}, \mu_{30}, \mathrm{L_{37}}$, and P are $\mathrm{M_\odot}$, 10^6 cm, 10^6 cm, 10^{30} G cm^3, 10^{37} ergs/sec and sec, respectively. By definition, ζ is the fractional solid angle subtended at the compact star by the infalling material at the magnetopause; $\mathrm{v_r/v_{ff}}$ is the ratio of the average material radial infall velocity to its free-fall velocity just outside the magnetopause; R, $\mathrm{R_g}$, μ, and P are the neutron star radius, gyroradius, magnetic dipole moment and rotation period. The quantities $\mathrm{M_x}$, R, and $\mathrm{R_g}$ are typically taken to be of order unity for neutron stars, as is the quantity $(\zeta v_r/v_{ff})^{1/7}$ (Lamb, Pethick and Pines 1973). Observed $\dot{P}$ values are inconsistent with white dwarfs being the compact object in the system.

X-ray pulsars allow the determination of the orbital parameters of the binary system from the Doppler delays of the pulse arrival times (Gursky and Schreier 1975). Such measurements have been made for about half of the systems. In several of these, the Doppler velocity curve of the primary is also measurable and, so, the mass of the secondary star can be determined (Rappaport and Joss 1983). To date, all are consistent with a 1.5 $M_\odot$ neutron star.

X-Ray Transients

A rocket-borne experiment in April 1967 (Chodil et al. 1968) found an intense, $L \sim 10\,L_{crab}$, X-ray source in Centaurus (where L is defined as luminosity and $L_{crab} = 1060\ \mu Jy = 2.5652 \times 10^{-9}\ ergs/cm^2\,sec\,keV$). This source had not been detected a year or so before to a limit of $0.3\,L_{crab}$ and was named Centaurus X-2 (Cen X-2). Observations after April found a steady decline in flux until it fell below detectability in late September. A paper by Francey et al. (1967) first associated the word "transient" with this type of behavior. Conner, Evans, and Belian (1969) reported the appearance of another new X-ray source near the boundary of Centaurus and Lupus, as found in the data of both the Vela 5A and 5B all-sky monitors. They noted similarities between their observation and what was then known about Cen X-2. In particular, based on the same sort of spectral softening and decay times, they concluded it (Conner, Belian, and Evans 1968, p. L158) "likely the same phenomenon is responsible for both sources." Other sources were found to exhibit the same type of behavior (3U1543−47, 3U1735−28) and by mid-1973 a new class of sources, the transients, was firmly entrenched in X-ray astronomy.

The Ariel 5 satellite, containing an all-sky monitor, was launched in October 1974 and found five more transient sources in its first year of operation. For the analysis of these data, Kaluzienski (1977, p.9) developed an empirical definition of a transient, to distinguish it as a class of sources from those considered "highly variable":

1.) Rapid rise ($t \sim 1$ week) to primary maximum followed by a gradual decline with time scale of 1–8 weeks (e-folding).
2.) Magnitude of outburst $L_{max}/L_{min} \sim 1000$, with $L_{min} < 1$ UFU.
3.) Mean interval between possible recurrent outbursts, $T_{rec} > 2$ yr.
4.) Preferential appearance at low galactic latitudes ($|b| < 5°$).

As the archives of X-ray astronomy began to develop a respectable baseline of time and detector sensitivity, this definition was called into question with just about every new paper. As an operational definition in the Uhuru satellite data analysis, Cominsky et al. (1978, p.1) used

> X-ray emission detected at an intensity well above the survey limit for an interval of length greater than 1 day which was short compared to the total amount of time the region was observed.

The recurrence of outbursts from a given source was becoming common; the detection of prolonged low-level emission between outbursts was becoming more common; the distinction between "highly variable" and "transient" was becoming vague. Bradt and McClintock (1983), in their Optical Counterparts of

Compact Galactic X-Ray Sources, characterized sources as transient if they satisfied a single criterion: the ratio of maximum to minimum recorded fluxes greater than 100.

Stella, White, and Rosner (1986) divided Population I binary transients into two classes based on their observational properties. In particular, the outbursts were divided into Class I—outbursts which recur periodically with $\mathrm{L}_{\max}/L_{\min} \sim 100$ and occurring close to times of periastron passage and Class II—outbursts which recur at random times, have $\mathrm{L}_{\max}/L_{\min} \sim 1000$ and with no correlation to orbital phase.

Perhaps a less observationally biased definition should be attached to the sources defined to be X-ray transients (the alternative being to get rid of the classification altogether in deference to "highly variable"). In what follows a look will be taken at the ten-year time histories of three massive binary systems considered to be X-ray transients as seen by the Vela 5B all-sky monitor. It will be seen that while all of these systems are B or Be/neutron star binaries, their behaviors are quite diverse and probably due to several different physical processes. One is apparently modeled by the capture of material in an evolving Be star envelope; another by enhancement of the Be star wind; and still another by some complex combination of processes. Some outbursts last for about 10 days, others last for about 100 days. Some recurrence times for a source are as little as 3 months, others as large as 10 years. The magnitude of each outburst varies as greatly for a given source as it does between sources—anywhere from a factor of 4 to a factor of 500 or more.

Our working definition, then, for a source to be termed "transient" will be

1.) Periods of enhanced X-ray emission which typically last for greater than a week, but which are not representative of the usual observed emission level of the source.

2.) Recurrences of an outburst by a source can be either periodic or aperiodic, but there is no obvious correlation between recurrence time and outburst amplitude.

It will be seen from the ten-year study of several massive binary systems that 1.) the behavior cannot be divided into separate classes based on temporal behavior or else previous definitions of "X-ray transient" would eliminate even those systems considered "classical transients" when monitoring is done continuously for long time periods, 2.) the physical mechanisms which must be involved in powering the observed outbursts are, in their simplest forms, complex combinations of the processes thought to be involved in these early-type systems, 3.) the change in pulse period or pulse shape when observed to evolve over several years (and several recurrences of a source) can lead to model constraints that may provide insight to a better definition or classification system for these sources (and certainly test the relationship between period change and mass accretion rate), and 4.) while several of the sources are binaries with orbital elements determined from spectroscopic observations or pulse timing studies, the orbital light curves of these systems (due to their transient nature) have been inaccessible to the previous observations. Whether an outburst occurs because of enhanced accretion at periastron or whether there may be two preferred phases for outburst (indicating some type of disk or circumstellar ring must be present) or whether outbursts are independent of orbital phase will provide another constraint on the source models.

CHAPTER II
DATA BASE REORGANIZATION

The Vela 5B Satellite

The Vela nuclear test detection satellites were part of a program run jointly by the Advanced Research Projects of the U.S. Department of Defense and the U.S. Atomic Energy Commission, managed by the U.S. Air Force. Six sets of Vela satellites were launched into nearly circular orbits at a geocentric distance of $\sim$ 118,000 km (18.5 $R_\oplus$). The satellites were launched in pairs and deployed 180° apart in a given orbit. The two Vela 5 satellites (designated 5A and 5B) were put into orbit 23 May 1969. The experiment design and implementation, with respect to Vela 5A and 5B, were done by W .D. Evans, J. P. Conner, R. D. Belian, J. A. Bergey, H. C. Owens, and E. R. Tech of Los Alamos and the staff of Sandia National Laboratory.

For Vela 5B, the data from which this dissertation is done, the orbital period was $\sim$ 112 hours. The satellite rotated about its axis, actively controlled to point toward Earth center, with a $\sim$ 64-second period. The X-ray detector was located $\sim$ 90° from the spin axis and, so, covered the celestial sphere twice per satellite orbit. Data were telemetered in 1-second count accumulations. A given source was viewed $\sim$ 2 seconds in a single spin for 4–10 hours in a single satellite orbit. Vela 5B operated until 19 June 1979, although telemetry tracking was sporadic after mid-1976. This time base for an all-sky monitor provides an unique resource for long-term variability studies such as those of Priedhorsky and Terrell (1983,1984). However, the data also present an unique opportunity for investigating the long-term period changes of pulsing sources, for monitoring recurrences in transient or flare sources, and many other desirable observations where a long data timeline is required.

The scintillation X-ray detector aboard the Vela 5B consisted of two 1 mil thick NaI(Tl) crystals mounted on photomultiplier tubes and covered by a 5 mil thick beryllium window. Electronic thresholds provided two energy channels, 3-12 keV and 6-12 keV. In front of each crystal was a slat collimator providing a FWHM aperture of $6.1° \times 6.1°$. The effective detector area was $\sim$ 26 cm^2.

Sensitivity to celestial sources was severely limited by the intrinsic detector background of $\sim$ 36 cts/s ($\sim$ 0.9 L_{crab}). The Vela 5B X-ray detector yielded $\sim$ 40 cts/s for the Crab, so 1 Vela ct $\sim$ 25 UFU $\sim 6. \times 10^{-10}$ $ergs/cm^2$ in the 3–12 keV response band. The wide collimation leads to source confusion in many interesting regions of the sky. However, good aspect information (± 0.2°) allows the deconvolution of individual source intensities in many cases. There are $\sim$ 50 sources detectable by Vela 5B.

Each Vela 5 satellite also carried six gamma-ray detectors. These detectors had a total volume of $\sim$ 60 cm^3 of CsI, responding to 150-750 keV gammas. It was in 1969 and 1970 that the Vela spacecraft first detected gamma-ray bursts. These bursts lasted a number of seconds, with a rapidly varying intensity on timescales of fractions of seconds. X-ray bursts on similar timescales were also found and several studies were done to find correlated gamma-ray and X-ray events. Two such events, GB 720514 and GB 740723, were reported by Terrell et al. (1982).

Several satellite performance characteristics previously unknown or unstudied were found during the course of this dissertation. One was a detector gain variation due to a ~ 60°C satellite temperature change from one side of the orbit to the other. In the telemetered datastream was a temperature monitor signal. This bit of information had long ago been edited from the data tapes, leaving the only remaining access to this information on several hundred rolls of microfilm which contained the original datastream in octal format. Using these listings and a monitor number-to-temperature conversion routine, the satellite temperature history could be recovered. The range covered, −3.2° to +58.4°C, had a non-trivial effect on the gain of the X-ray detector. The effect was seen to follow the expected highest-gain-for-lowest-temperature trend; however, lack of pre-launch testing precludes any quantitative post-launch compensation. As a result, if a particular observation is made at either temperature maximum or minimum, the absolute flux is unusable (Figure 2-1). The temperature sensor failed on 23 June 75, but the trends were well enough established by then to allow projection forward to all subsequent time (Figures 2-2 and 2-3).

Degradation of the satellite orbit over the ten years of operation also turned out to be significant. The orbit was fairly stable after launch through mid-1974, but degraded from a slightly elliptical to a highly elliptical one after that. In fact, by 1979, the satellite ranged from 16.8 $R_\oplus$ to 20.09 $R_\oplus$ over the course of a single orbit. This could introduce an error in the barycentric time correction of order 0.03 seconds if not accounted for. More will be said about this in the analysis program section.

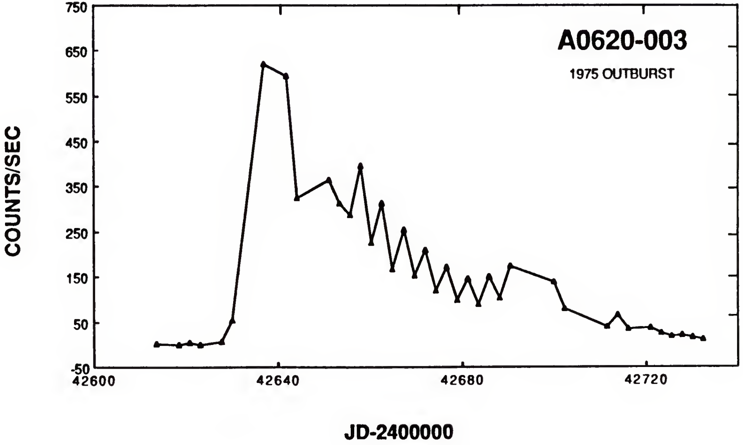

Figure 2-1. Effect of the satellite temperature variation of the data when data are taken during times of temperature maximum and minimum. The sawtooth structure on the decline of this 1975 outburst of the source A0620-003 is the result of this variation effecting the detector gain.

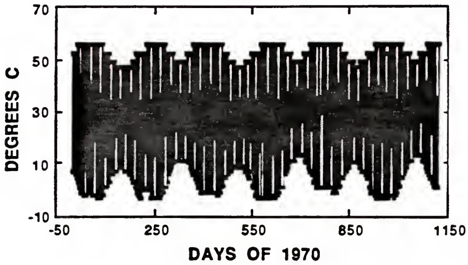

Figure 2-2. Time history of the satellite temperature variation from Jan 1970 - Apr 1975. Evident is the effect of the ~300-day satellite orbit precession.

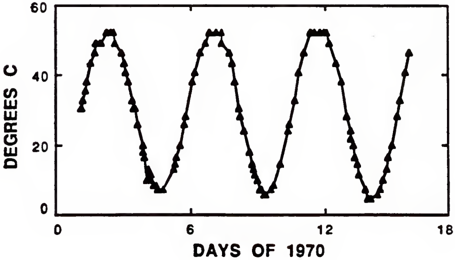

Figure 2-3. Time history of the satellite temperature variation Jan - Apr 1970 showing the 112-hour periodicity (1 satellite orbit) in the modulation.

NOS to VMS Conversion

The Vela 5B X-ray data resided at Los Alamos on 36 magnetic tapes in a time-ordered format. Programs to read and analyze the data were written in Fortran 4-Extended and run utilizing NOS (Network Operating System) on a Cyber 725. To access the data for a single X-ray source for the 10 year observation history required the mounting and reading of all 36 tapes. The inconvenience and expense of this allowed analysis exploiting the full 1-second resolution of the data feasible for only a few, select sources. Therefore, a major reorganization effort was made to allow easier access to the data base. There were two main objectives: 1.) conversion of the data base into coordinate order and 2.) transfer of the data base into a VAX readable format. This work is described in detail below.

A flow diagram of the computer program used to transfer the data to a VMS– compatible format and prepare it for time-to-coordinate order conversion is shown in Figure 2-4. This code runs on the Cyber 725. The driver of the code reads in the time-ordered data, performs various systematic corrections to it (such as correction for the 89.8° angle of collimator direction and a 1-second timing error), and throws out obviously poor data (such as during times of passage through the earth's magnetotail or solar flares). If the data are considered acceptable, a background fitting routine is called. This 'background' is due to internal detector counts and low-level diffuse cosmic sources. The subroutine fits the function

$$y(t) = a(t)\cos\omega t + b(t)\sin\omega t + c(t) \tag{1}$$

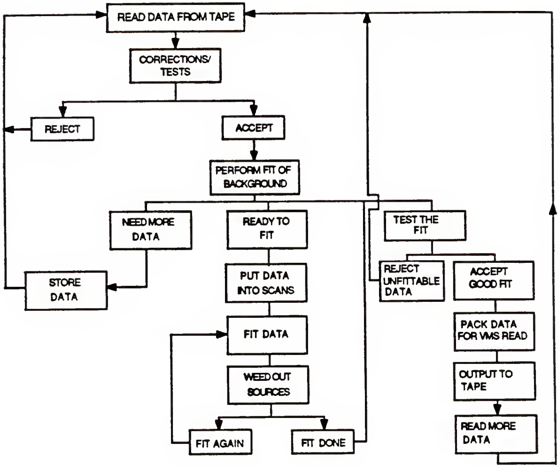

Figure 2-4. Flow diagram of the computer code used to convert the data from NOS to VMS and prepare it for conversion from time to coordinate order.

to a 64-point ($\sim$ 1 spin) span of data that is the average of five 64-point consecutive spans. Average values are used to reduce noise in the fit. Points $\pm 2.5\sigma$ away from the average value obtained from the weighted sum across the 64-point span (such as would be the case for a source,etc.) are thrown out and the fit redone until no more points are removed. Also removed from the fit are any data in certain given coordinate boxes which are known to be affected by persistent X-ray sources. The sources considered are Aquila X-1, Serpens X-1, the Crab, Vela X-1, Scorpius X-1, the 3-source Cygnus region, the Centaurus-Crux region (bounded by $l = 283°$ to $313°$, $b = -10°$ to $+10°$), and the galactic bulge region (15 sources were included). A map of excluded regions is shown in Figure 2-5. The variance on each fit coefficient as well as the probability of getting the χ^2 found for each final fit is put into the data stream to be written to tape. Thus, a measure of how good the background fit is for each datum will be retained with that datum. The logic behind not including the covariances in the datastream is given in Appendix B. The fit must then pass certain average and variance tests of quality assurance or it will be rejected. If the data are rejected, the program goes back to the start of the background fitting routine and reads in another 64 second span. If the data are accepted, they are prepared for output to tape. All values are integerized in order to transfer them correctly from NOS to VMS. The data are then packed into an array (see Appendix A for details) which is dumped out to tape when full. The program returns to the start of the subroutine to process the next 64-point span, unless it has done them all and, then, it returns to the start of the program code and reads in the next data array from the input tape.

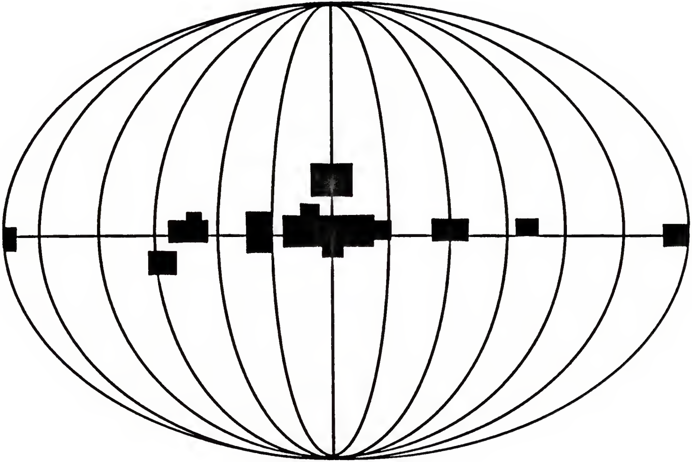

Figure 2-5. Map of the areas whose data are automatically excluded from the background fitting routine.

In the data stream output to tape, each second of data has associated with it the following information:

Coordinate box number - integer generated from the Ra and Dec of the observation.
Year, day of year - of the observation
Seconds - of the observation
RA - of the observation
DEC - of the observation
XC1 - counts in Channel 1
BKG1(1) - background fit coefficients for Channel 1
BKG1(2)
BKG1(3)
IPOS1 - position of the point in the 64-point span fitted
XC2 - counts in Channel 2
BKG2(1) - background fit coefficients for Channel 2
BKG2(2)
BKG2(3)
IPOS2 - position of the point in the 64-point span fitted
RAA - right ascension of spacecraft axis
DECA - declination of the spacecraft axis
SPFLAG - flag to indicate spin period stability
PEFLAG - flag to indicate pointing error
BKVAR(1) - variance of background fit coefficients for Ch1.
BKVAR(2)
BKVAR(3)
PROB(1) - probability of chisq for bkg fit for Channel 1
BKVAR2(1) - variance of background fit coefficients for Ch2.
BKVAR2(2)
BKVAR2(3)
PROB(2) - probability of chisq for bkg fit for Channel 2
SPINP - spin period of satellite at time of observation

By associating the time of observation and detector count rate with all of the information listed above, each observation would then be "independent" in that it would have associated with it all of the necessary data to perform all of the temporal systematic corrections without having to have the other data points from the particular satellite spin in which the observation occurred still connected to it. Thus, the conversion from time order to celestial coordinate order could be accomplished. The coordinate box number is the value which is used to convert the data base into coordinate order by the VAX programs described in the next section. The celestial sphere is divided into 11984 boxes, each box being roughly $2° \times 2°$. To complete the reorganization, the task was one of ordering the data from magnetic tapes based on the box number tagged to each 1-second datum.

Several factors constrained the procedures for accomplishing the task. One was available memory space. One VAX disk holds about 890,000 512-byte blocks of data (4.5×10^8 bytes); one magnetic tape, written at a density of 6250 bits per inch, holds 1.8×10^8 bytes of data. Another constraint was the maximum number of simultaneously open files allowed by VAX/VMS Fortran (i.e., 99).

A two-stepped approach was chosen. First, the data would be broken up into a series of tapes, each having a variable, but unique sequence of pseudo-randomly ordered coordinate boxes. Each NOS-generated tape was read, with the box number associated with each observation used as a trigger. If the number fell between certain set values, it was written to a certain output tape. If it fell between another set of values, it was written to a different output tape. A diagram of the process is shown in Figure 2-6. This division was continued until a given series of boxes was located on only one magnetic tape.

The data from one magnetic tape fits easily onto one RA-81 VAX disk. The approach, then, was to read in a tape, use the VAX/VMS "SORT" utility to sort the data by box number and create a disk file where all the BOX 1 data were followed sequentially by all the BOX 2 data and so on. Subsequently, a program

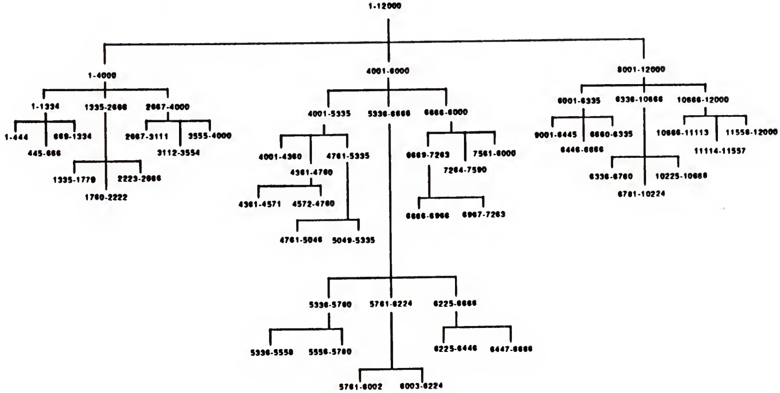

Figure 2-6. Diagram showing the division of the coordinate boxes on each tape into a series of tapes which contain an unique set of boxes.

would be run to open a data file for a given box, read the disk file, close it when the box number was seen to change, and write the reformatted file to an output tape. The result was a set of 24 magnetic tapes with the data ready for access by the analysis programs. This completed the Vela 5B data reorganization into a VAX-residing, coordinate-ordered, 1-second resolution data base.

Access and Analysis Programming

A code was written to access the data base in a user-friendly manner and to provide general analysis routines—such as binning, epoch folding, discrete Fourier transform, hardness calculation, etc. A flow diagram of the code is shown in Figure 2-7. A number of flexible plotting routines are included to allow the program operator to achieve a plot of whatever is desired. The code is menu driven. The main menu includes

CMDS - prints the menu of available options
TAPE - allocates tape drive for reading in data from tape
STRT - allows reading in from tape data from user selected source
BIN - bins data into user selected,variable binning times
RDF - reads data in from disk file
WRTF - writes data out to a disk file
PLOT - takes user to plotting menu
DFT - allows discrete Fourier transform of data
SAVE - saves current data in storage arrays
RECL - recalls data from the storage arrays
FOLD - allows epoch folding of the data
HARD - takes ratio of 6-12 keV to 3-6 keV data points
TIME - removes binary motion effect from data, corrects to barycenter
TEST - randomly scrambles data to allow significance tests to be run
QUIT - ends execution of program

The 'PLOT' menu contains the following options:

CMDS - prints the menu of available options
PLOT - plots data in active data array
OPLT - overplots data in current and storage data arrays

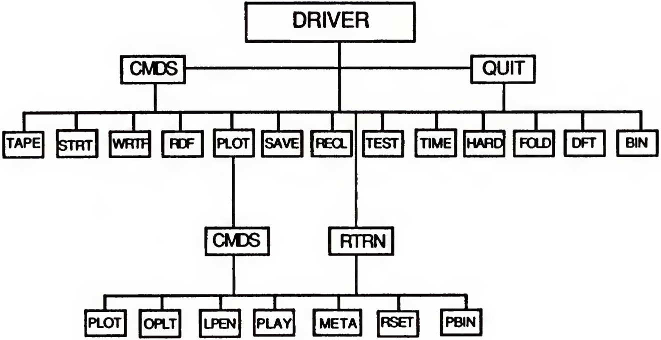

Figure 2-7. Flow diagram of the access and analysis program for use on the reorganized database.

LPEN - allows cursor mode selection of segments of plotted data
PLAY - same as LPEN, but allows 10 cursor selections
META - opens meta file into which all subsequent plots will be written
RSET - restores all of original data to active use
PBIN - plots data binned in main part of program
RTRN - returns user to main menu

The time variability studies which are done in this dissertation are accomplished through the application of the following well-established analysis techniques. In order to retain phase coherence for periodicities of order a few to a few hundred seconds when using months to years of data, it is necessary to correct the observation times to a more stationary point than the Vela 5B satellite, namely, to the solar system barycenter. Values for the longitude of ascending node and perihelion, mean distance, inclination, eccentricity, and mean anomaly are taken from The American Ephemeris and Nautical Almanac - 1974. Values for the ratios of the mass of the Sun to planetary masses are the values accepted in 1976 by the IAU for use starting in 1984 ephemerides publications. The code was compared to an ephemeris prediction code written by Dr. John Middleditch of Los Alamos National Laboratory to run on a Cray which is known to generate a barycentric correction good to 1 part in 10^3. The results agreed to within this error. As mentioned in the satellite section earlier, the Vela 5B orbit was nominally circular the first 4.5 to 5 years of its life. Thus, using an average orbital radius of 18.46 $R_\oplus$ introduced an error of order 1 in 10^3, i.e. the same as the accuracy of the barycentric correction to that point. However, after the year 1974, this error becomes larger with each passing year—finally reaching 3 in 100 by 1979. From examining the orbital radius records, it was clear that no simple algorithm would lead to a noticeable improvement in the result. So the error in the timing correction routine is allowed to change over 1969–1979 from 1 in 10^3 to a few in 10^2. Since the data have 1-second resolution, this is acceptable. Also note that the time frame in which the correction is least accurate coincides with the reduction in data coverage due to poor satellite tracking.

Periodicities can be searched for using either discrete Fourier transforms or epoch folding. The discrete Fourier transform routine in the program allows a choice between the Deeming algorithm or the Kurtz approximation of the Deeming algorithm (Deeming 1975; Kurtz 1985). Tests were run comparing the two and no difference was found with the exception of runs with extremely long data timelines. Here the cosine error introduced by the Kurtz approximation could be seen, but not to a significant order. The run time of the Kurtz routine is about 1/3 that of the Deeming algorithm. The epoch folding routine is the standard one of generating a χ^2 from a fit of the folded light curve to a constant. This routine is especially useful in finding phenomena using short stretches of data, often yielding significant results when transforms could not.

CHAPTER III
MODELS

The OB stars typically have masses of 10 – 20 $M_{\odot}$ and are known to lose mass via a stellar wind, typically with mass loss rates of 10^{-6} $M_{\odot}$ yr^{-1}. A neutron star companion to such a star will capture a fraction of this wind, accrete it, and, thereby, produce X-rays. In the case where the OB star is a supergiant, typical binary separations of 1.5 – 2.0 $R_{\odot}$ imply that the neutron star is well imbedded in the wind. In contrast, the main sequence OB binaries tend to have wider separations and other mechanisms must be found to provide a sufficient amount of material to the neutron star for accretion. For the Oe and Be stars, the known phenomena of shell emission, dense circumstellar envelopes, and sudden equatorial mass ejection all can provide the necessary material. Of the $\sim$ 30 such systems known, the Vela 5B satellite can detect 5 of them with sufficient intensities for analysis. The 3 sources chosen for this study are representative of the various types of behaviors observed in these binaries.

The time-averaged X-ray luminosity resulting from direct wind accretion is governed by the wind characteristics at the accretion radius of the neutron star. This radius is defined as the distance at which the wind material is gravitationally captured by the compact object. Assuming that all of the gravitational potential energy is converted into X-rays leads to the relation of the X-ray luminosity as a function of the wind parameters (Stella, White, and Rosner 1986):

$$\mathrm{L_x \sim 4 \times 10^{35} R_x^{-1} M_x^3 M_\star^{-2/3} P_o^{-4/3} \dot{M}^{2/7} v_0^{-4}} \quad \mathrm{ergs\ sec^{-1}}$$

where $\dot{M}$ is the OB star mass loss rate in units of 10^{-8} $\mathrm{M_\odot}$ /yr, $\mathrm{M_\star}$ is the OB star mass in units of 10 $\mathrm{M_\odot}$, R_x is the neutron star radius in units of 10^6 cm, M_x is the neutron star mass in units of 1.5 $\mathrm{M_\odot}$, P_o is the orbital period of the system in days, and $\mathrm{v_0}$ is the wind velocity at the accretion radius. Obviously, the X-ray luminosity is highly dependent on the velocity of the material approaching the compact object. If some mechanism can reduce the terminal velocity of the wind, a much higher X-ray luminosity can be achieved.

In an effort to explain the high luminosities observed, Ho and Arons (1987) investigated the effect of X-ray "feedback" onto a radiation-driven wind in a binary system. It was found that the X-rays feed back onto the incoming wind to control the ionization and, therefore, the all important terminal wind velocity. Making several simplifying assumptions to make the problem mathematically tractable, Ho and Arons showed that a self-consistent equation can be established with multiple solutions to the steady-state. One of these, the low-luminosity solution, is simply direct stellar wind accretion. Another of these, the high-luminosity solution, brought the observed X-ray fluxes of OB giant and supergiant binaries, such as Cyg X-1, Vela X-1, and SMC X-1 into good predicted agreement. It should be noted that these three binaries all have fairly circular orbits and, so, the wind velocity and density being sampled by the neutron star is constant around an orbit. Other simplifying assumptions made included

1.) corotation of the wind, such that there is only radial motion in the frame corotating with the primary, 2.) no effects from the X-ray heating of the incoming wind material, and 3.) no effects from the X-ray radiation pressure. The physical implications and appropriateness of these assumptions will be discussed further in a later chapter.

Avni and Goldman (1981) used the known observations of the Be/neutron star binary 4U0115+63 in a discussion of stellar wind accretion in widely separated binaries. They pointed out that normal wind accretion could easily account for the steady-state or quiescent luminosity values that had been observed. However, for typical OB star wind parameters, luminosities no greater than 10^{33} ergs/sec could be achieved while values of $\geq 10^{37}$ ergs/sec are observed during outburst. Using the more gradual wind profile equation of Barlow and Cohen (1977) (in contrast to the more widely used velocity profile of Castor et al. 1975), luminosities of order 10^{36} ergs/sec could be achieved, but only if the mass loss rates are an order of magnitude higher than those measured for typical Be stars. Furthermore, neither wind velocity profile can reproduce the observation of both the lack of orbital period modulation due to an appreciable orbital eccentricity and the absolute luminosity of $\geq 10^{37}$ ergs/sec of the source during outburst. A mediating accretion disk was proposed to overcome several of these difficulties. This idea is also consistent with the spin ups seen in many of the outbursts. Based on optical observations of the primary , V635 Cas, which showed an increase of 1.7 mag about 60 days before the 1980 X-ray outburst of 4U0115+63, Kriss et al. (1983) also used a mediating disk in a model for the system. Again, lack of orbital modulation and – in this case – the delay length between optical/X-ray emission, precluded any sort of direct wind accretion. The delay timescale would represent the timescale for material to move inward from an accretion disk to the neutron star surface through the action of viscous forces. This would allow the calculation of α, the viscosity parameter, if the steady-state α-disk model (Shakura and Sunyaev 1973) is used. In fact, for canonical neutron star parameters, α would be less than 1. A limit can also be assigned to the disk radius of $\sim 10^{11}$ cm and a primary mass loss rate of $\sim 10^{-9}$ $M_\odot$/yr. It should be recalled that the X-ray event lasted only about 1/3 as long as the optical event. Thus, the disk would have to be temporary and the steady-state α-disk is not truly applicable.

The identification of the optical companions of many of the massive X-ray transients as Be stars provides another potential source of material for the neutron star to accrete, namely, the circumstellar envelope most Be stars are known to possess. Accretion of this material, which is strongly concentrated in the equatorial plane and has typical outflow velocities and densities of ~ 100 km/sec and 10^7 /cm^3, respectively, at a distance of 5×10^7 km (see van den Heuvel and Rappaport 1987 and references therein), would result in a persistent X-ray flux of $\leq 10^{35}$ ergs/sec. Furthermore, it can be shown that only unreasonable changes in such an envelope, with extreme values for the material density or outflow velocity, could produce the luminosities observed during outburst.

In an altogether different approach, Stella, White and Rosner (1986) investigated the possibility of intermittent stellar wind accretion in Population I binary systems containing an X-ray pulsar as the physical model for known X-ray binary transients. They used V0332+53, and to a lesser extent 4U0115+63, as an example for their idea. The aim was to be able to explain both the random long term behavior of this class of sources and the repetitive short term behavior. They define regimes of accretion based on the pulse period of the source and the relative magnitudes of the accretion, corotation and magnetospheric radii. The accretion radius, r_a, gives the maximum impact parameter for wind capture by the neutron star; the corotation radius, r_c, is the radius at which the pulsar corotation velocity is equal to the Keplerian velocity; the magnetospheric radius, r_m, is the radius at which the neutron star magnetic field pressure is equal to the ram pressure of the accreting wind. In regime I, $r_a, r_c > r_m$ – which leads to direct wind accretion. In regime II, $r_a > r_m > r_c$. As a result, wind material that passes through the accretion radius hits the magnetospheric radius and is stopped. The material can then either be ejected via something like the "propeller effect" or else can accumulate in a ring outside the magnetospheric radius. In regime III, $r_m > r_a$ and so the stellar wind flows around the neutron star magnetosphere, allowing little if any accretion to occur.

The relative magnitudes of the radii involved, and therefore the accretion regime, are determined by the mass loss rate of the primary, $\dot{M}_*$, and the wind velocity, V_o. This parameter, gamma, is defined as

$$\gamma = \left(\frac{\dot{M}_*}{10^{-8} M_\odot \mathrm{yr}^{-1}}\right) \left(\frac{V_o}{10^8 \,\mathrm{cm\,s}^{-1}}\right)^{-4}$$

If γ is small (for typical Be systems, < 90), the source will be in its dormant state due to centrifugal inhibition of accretion. If an increase in mass loss rate, decrease in wind velocity, or both increases γ to a value of $\sim$ 100–400, the source will overcome the centrifugal barrier and become active at an orbital phase centered on periastron. However, there will not necessarily be enough accretion enhancement for the source to be X-ray bright around an entire orbit.

A larger increase in γ (to a value of > 400) will allow the X-ray pulsar to be active through all orbital phases. This mechanism thus provides a natural explanation for the outbursts centered on periastron (source in regime I, $\gamma = 100$–400), the outbursts with no orbital modulation (source in regime I, $\gamma > 400$) and the long dormant periods between the recurrences (source in regime II).

The Be star phenomenon of eruptive mass loss can provide the material necessary to change the value of γ by orders of magnitude and thus reproduce the observed X-ray luminosities and light curves. This model can then be applied to the large change in luminosity, the delay between optical and X-ray enhancement, and the relative lifetimes of the optical and X-ray behaviors. The primary mass loss associated with the initial optical enhancement would not necessarily have been enough to cause the magnetospheric radius to move inside the corotation radius. However, the mass could be captured in a ring as described above and eventually the pressure of the accumulating incoming material would be sufficient to overcome the centrifugal barrier and the X-rays would turn on. The ring reservoir would be drained as the pulsar moves around its orbit and eventually the incoming mass would no longer exert sufficient pressure to maintain the $r_m < r_c$ criterion even though mass loss is still occurring. As a result, the X-ray flux diminishes while the optical flux remains enhanced.

Illarionov and Sunyaev (1975) were actually the first authors to suggest a centrifugal "barrier" as a mechanism to 1.) lessen the number of X-ray emitting stars expected by stellar evolution theory–and in accord with the number of X-ray systems actually observed and 2.) provide a mechanism which could account for the long period (of order of hundreds of seconds) X-ray pulsars. This latter characteristic was due to the spin down induced by material being expelled by the barrier, i.e. the "propeller" mechanism. This idea was further developed by Wang and Robertson (1985) with regard to the timescales necessary for such a mechanism to produce a 100 second pulsar relative to the main sequence lifetimes of OB stars. It was found that this mechanism, when slightly modified, could produce an appropriate spin down on timescales of 10^6 years–well within the main sequence lifetimes of these stars. Applying the equation (Wang and Robertson 1985)

$$P/\dot{P} \sim 10^6 \left(\frac{M}{M_\odot}\right) \left(\frac{10^{12} G}{B_o}\right)^{4/5} \left(\frac{10^6 \mathrm{cm}}{a}\right) \left(\frac{1\mathrm{s}}{\mathrm{P}}\right)^{2/5} \left(\frac{10^{-13} M_\odot \mathrm{yr}^{-1}}{\dot{M}_\odot}\right)^{3/5}$$

for the spin down time given the measured spin down and pulse period, a value for the mass capture rate can be found. For the canonical parameters of 4U0115+63 (i.e. a = 10^6 cm, $B_o = 1.8 \times 10^{12}$ G,$\mathrm{M_x} = 1.5\ \mathrm{M_\odot}$), a mass accretion rate of $\sim 10^{-12} M_\odot/\mathrm{yr}$ is necessary to produce the observed $\dot{\mathrm{P}}$–a value too low to be given much credibility. Be star mass loss rates in the equatorial regions as derived from Hα line profiles and IR excess by Poeckert and Marlborough (1979) are typically of order $10^{-8} M_\odot/\mathrm{yr}$. Thus, an accretion efficiency of 10^{-4} would be required, when 0.1 is the typical value for neutron stars. However, if the neutron star is in the inhibited accretion regime, such values may not be so unreasonable and thus provide a natural explanation for the spin downs observed between the outbursts of several X-ray transients.

Several mechanisms have been considered as the driver of the Be star instability which leads to eruptive mass loss. The most commonly accepted is a correlation of the mass loss with the rapid rotation observed in most Be stars. Assuming that rapid rotation produces instabilities, then, according to the Jeans hypothesis, matter will be ejected at the equator of the flattened body of the star. Penrod (1986,1987), Baade (1987) and other researchers have investigated non-radial pulsations as a potential driving mechanism for the transient nature of the Be star/neutron star binaries. They have shown that high-order nonradial pulsations are present in the observations of several Be stars. Sporadic release of the pulsation energy could be responsible for the "Be star phenomenon"– i.e. the ejection of blobs of mass from the equatorial region of the star or the ejection of a shell. If these oscillations grow large in amplitude, they could become strong enough to modulate the outflow of the stellar wind, thus determining γ. The frequency of the nonradial mode might then be captured in the mass accretion rate process and show up as an X-ray periodicity, with periods ranging from 2–30 hours. Pesnell (private communication 1987) subsequently showed that the Be star cannot modulate the mass loss via a non-radial pulsation strongly enough to induce a corresponding modulation in the X-rays from accretion by the neutron star (as has been suggested by Penrod and others). The effect of the non-radial mode is lost outside of the wind acceleration radius, i.e. $V_{\mathrm{wind}} < V_{\mathrm{term}}$ to preserve the integrity of the mass loss modulation. This condition is not met at any time during the orbit of any non-contact binary. However, this mechanism could be responsible for a blob of material leaving the Be star to force the neutron star from an inhibition into an accretion regime.

All of the above models, simple wind accretion, X-ray feedback on simple winds, accretion from a circumstellar envelope or shell or equatorial mass ejection, and the centrifugal inhibition of accretion, can be tested by the ten years of data for several of the massive binaries observable in the Vela 5B data base.

CHAPTER IV
OBSERVATIONS AND DISCUSSION

4U0115+63

Introduction

Four outbursts have been observed for the X-ray transient 4U0115+63: 1970-71 by Uhuru, 1978 by SAS-3, Ariel 5 and HEAO 1, 1980 by Ariel 6, and 1987 by Ginga (Forman et al. 1976; Cominsky et al. 1978; Holt and Kaluzienski 1978; Johnston et al. 1978; Ricketts et al. 1981; Makino et al. 1987). A 3.6 second pulse period was discovered in the 1978 event (Clark and Cominsky 1978), allowing the 24.3 day orbital period and the other orbital elements of the system to be determined (Rappaport et al. 1978). The published observations are summarized in Table 4-1. The optical companion was suggested to be a heavily reddened B star (Johns et al. 1978) and optical brightenings ~ 30–80 days before both the 1980 and 1987 X-ray outbursts (Kriss et al. 1983; Mendelson and Mazeh 1987) confirmed this identification. A search of the Vela 5B data base reveals that the source also underwent a major outburst in August 1974 and small outbursts in August 1969, January 1970, and August 1970. This paper presents an analysis of these observations.

Observations

The ten-year time history of 4U0115+63, shown in Figure 4-1, has several interesting features. The previously reported outbursts in January 1971 and

TABLE 4-1

Summary of Observations of 4U0115+63

Time	Maximum Intensity (Crab)	P_s (sec)	Hardness (6–12/3–6 keV)	Refs.	Comments
Aug 69	0.38	———	0.78 ± 0.11	8	
Jan 70	0.23	———	0.85 ± 0.26	8	
Aug 70	0.22	———	0.75 ± 0.11	8	
Jan 71	0.17	3.61464	0.85 ± 0.20	7	double peak
Jan 71–July 1972	0.02	———	———	1	quiescence
Aug 74	1.8	3.6142	1.09 ± 0.06	8	
Jan 78	0.6	3.6145737	$1.24\sim 1.60$	2,6	
Aug 80	$< 2 \times 10^{-5}$	———	———	4	quiescence
Dec 80	0.15	3.6146643	———	3	
Feb 87	0.18	———	———	5	

REFERENCES.—(1) Forman et al. 1976; (2) Johnston et al. 1978; (3) Ricketts et al. 1981; (4) Rappaport 1980; (5) Tsunemi and Kitamoto 1988; (6) Rappaport et al. 1978; (7) Kelley et al. 1981; (8) This paper.

December 1977–January 1978 are apparent. In addition, there are four other outbursts in the data. These occur in August 1969, January 1970, August 1970, and August 1974. The four small outbursts in 1969–1971 are roughly 180 days apart (Figure 4-2). The outbursts starting in 1971 and continuing to the present recur at intervals of 2.9–3.5 years.

The four small outbursts August 1969–January 1971 had rise times of 3–7 days. The first event was above an average Vela threshold of 1 ct/sec for $\sim$ 14 days, the second $\sim$ 10 days, the third $\sim$ 28 days, and the fourth $\sim$ 30 days. The maximum observed intensity for each outburst was 0.35 Crab, 0.19 Crab, 0.17 Crab, and 0.16 Crab, respectively, based on 56-hr averages in the 3–12 keV channel. There is evidence that the source had a measurable average intensity between the August 1970 and January 1971 events of $\sim$ 0.03 Crab. The latter event had a double peaked light curve, with the maxima separated by 25. ± 2.0 days or approximately 1 binary period. This is the only outburst of this source clearly observed to have such a feature. It was after this event that Uhuru detected a low-level emission of 0.02 Crab which persisted for roughly a year. During all four of these outbursts, there was non-periodic variability on all timescales available to Vela 5B. Flares were observed which lasted for about 10 minutes, achieving maximum count rates comparable to that of the Crab, as well as less intense flares which lasted for 1-3 hours. The maximum intensity for each of the four outbursts occurs at an orbital phase of 0.55 ± 0.1 (i.e. near apastron). This is not easily understood from a theoretical standpoint as at this phase any Be star envelope or wind being sampled by the neutron star would be most tenuous. The average hardness ratio (6–12 keV/3–6 keV) for each outburst is 0.78 ± 0.11, 0.85 ± 0.26, 0.75 ± 0.11 and 0.85 ± 0.20–with the ratio remaining

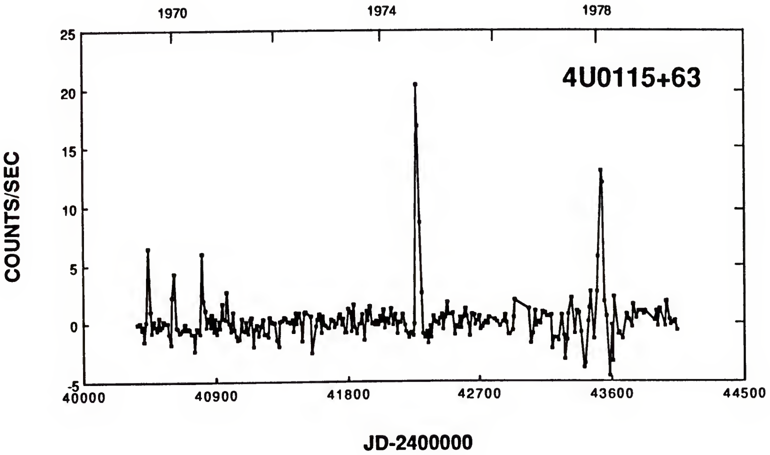

Figure 4-1. Time history of 4U0115+63 1 June 1969–15 June 1979 (JD2440373–JD2444039) as seen by Vela 5B in the 3–12 keV energy channel. Each point represents a 9.33 day average (2 satellite orbits).

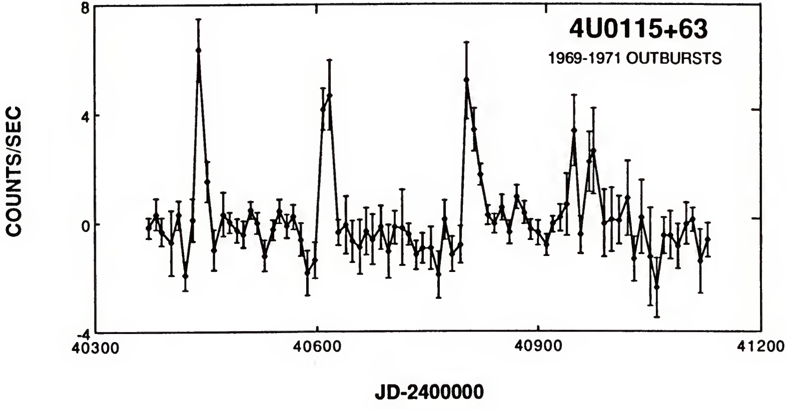

Figure 4-2. Time history in the 3–12 keV channel for 1 June 1969–7 April 1971 (JD2440373–JD2441048) showing four low-intensity outbursts, the last being double-peaked. Each point represents a 9.33 day average.

approximately constant throughout the events. For comparison, the Crab had an average hardness ratio of 0.58 ± 0.01 during the same period. These values are slightly softer than the values observed for the other outbursts, which were all in the range 1.1–1.5.

The mid-1969 to mid-1971 data hint at a periodicity at the binary period in both the outbursts and quiescent flux. A discrete Fourier transform of these data reveals a peak at 24.3 days. Transforms of later time sequences do not contain a similar peak. Poor statistics and certain systematic effects are such that the probability of a random occurrence of such a peak at the expected frequency is $\sim$ 1%. The significance of the peak is the same whether or not the four small outbursts are included in the transform. In each case, the maximum continues to occur at phase $\sim$ 0.5.

The source again became detectable on 6 August 1974 (Figure 4-3) and reached a maximum intensity on 11 August of 68.6 ± 12.4 cts/sec in Channel 1 (3–12 keV) and 28.0 ± 6.4 cts/sec in Channel 2 (6–12 keV) which correspond to S $\sim$ 1.8 Crab and S $\sim$ 1.9 Crab, respectively. The intensity then gradually declined until it fell below Vela threshold on 6 September. At a distance of 5 kpc (Johnston et al. 1978), a value of 1.8 Crab corresponds to a luminosity of $\sim 9 \times 10^{37}$ ergs/sec. There were brief brightenings in the averaged light curve on 27 August and 1 September which were mostly the result of several strong, $\sim$ 10 minute long flares during these observational sequences. This flaring is similar to that observed in the small outbursts 1969–1971. The average hardness ratio was 1.18 ± 0.05 and remained roughly constant throughout the event. Variations are seen in the hardness ratio on 1-sec timescales and are most likely related to the pulse phase of the source, as observed by Johnston et al. (1978) in the

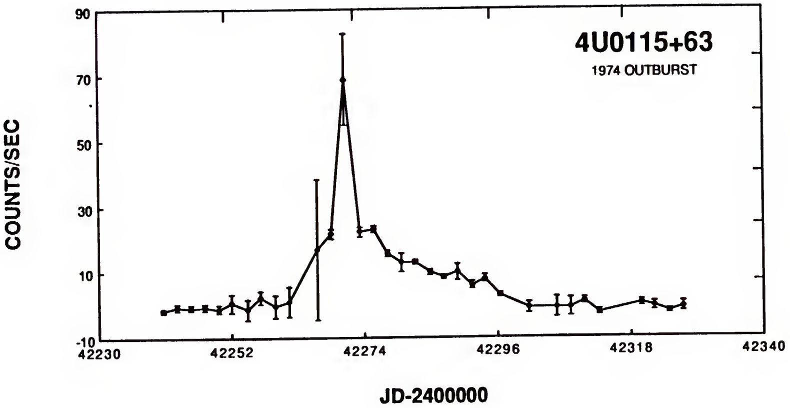

Figure 4-3. Time history of the August 1974 outburst. Shown are data from 12 July – 7 October (JD2442240 – JD2442327). Each point represents the average of a single satellite observation sequence in the 3–12 keV channel. These sequences recur every 56 hours.

1978 outburst. However, large statistical errors make a detection of the 3.6 sec pulsations in the hardness ratio impossible.

The limited coverage of the December 1977–January 1978 outburst (Figure 4-4) yields a maximum intensity on 9 January of 0.6 Crab, based on 56-hr averages. This value is consistent with the single high point reported by Rose et al. (1979) using Ariel 5 SSI data for that date. This observation is well outside of the average outburst envelope and, even though Vela coverage is sparse at this time, is consistent with the $\sim$ hour long flares seen in the previous events. Unfortunately, no other Vela 5B data were recorded for three satellite orbits before or two orbits after this date. The average hardness ratio based on these same averages is 1.13 ± 0.15, which is consistent with the published HEAO 1 scanning modulation collimator experiment data hardness ratio (5.4–13.3 keV/2.6–5.4 keV) of 1.24–1.6 for this outburst (Johnston et al. 1978).

After correction to the barycenter and for the binary Doppler effect (based on best parameters of Rappaport et al. 1978; Kelley et al. 1981), both discrete Fourier transform and epoch-folding of both energy channels of the Vela 5B data reveal a pulse period of 3.6142 ± 0.0001 seconds for a 6.6 hour stretch of data on 23 August 1974. At that time, the source luminosity was 1.88×10^{37} ergs/sec (3–12 keV at 5 kpc). The folded light curve for this period is shown in Figure 4-5. The formal probability of finding a random Fourier peak in the frequency range searched, in the five observational sequences searched, with a power equal to the 3.6142 sec peak found in the Channel 1 transform is $\sim 2.5 \times 10^{-3}$. A value of 3.6142 sec implies a period change (spin up) between the 1971 and 1974 outbursts of -3.4×10^{-5}/yr. The 3.6 sec pulsations can be seen only in this particular observational sequence of 1974 outburst. The fluxes of other sequences during

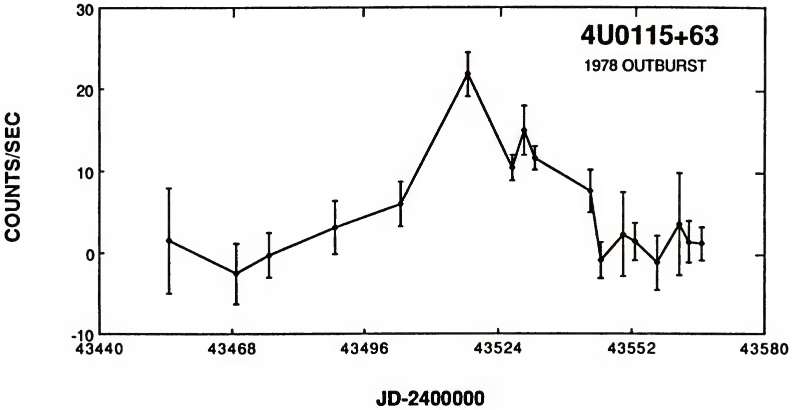

Figure 4-4. Vela 5B observations of the 7 November 1977 – 28 January 1978 (JD2443454 – JD2443567) outburst in the 3–12 keV channel. Each point represents the average of a single satellite observation sequence. Coverage of the event was poor due to sparse telemetry tracking.

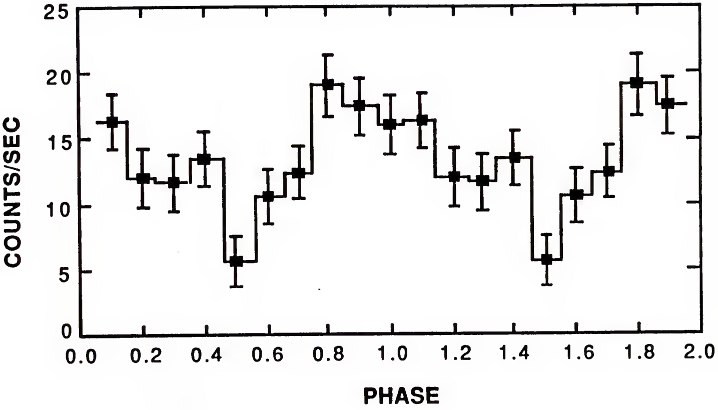

Figure 4-5. The average pulse profile of 4U0115+63 in the 3–12 keV channel. The data used are from 23 August 1974 and have been folded modulo the best fit period of 3.6142 sec.

this event and the other outbursts are either too weak for Vela 5B to detect a modulation or incomplete telemetry tracking makes the statistics too poor for a positive detection.

Discussion

Adding four new outbursts and a detection of the pulse period during the 1974 event to the observational history of 4U0115+63 adds new constraints to models for the transient eruptions. Among the various models proposed have been simple stellar wind accretion, temporary accretion disks, and intermittent wind accretion by a neutron star in orbit around a Be star.

Simple wind accretion in an early-type, widely separated binary was the first mechanism suggested to model the X-ray behavior of 4U0115+63 (Avni and Goldman 1981). While this model can easily account for the quiescent or steady-state luminosity observations, it predicts a strong orbital modulation due to the orbital eccentricity ($\epsilon = 0.34$) and luminosities no greater than 10^{33} ergs/sec for typical B star winds ($V_{wind} < 2000$ km/sec, $\dot{M} < 10^{-7}$ $M_{\odot}$/yr). However, no orbital modulation is observed and peak luminosities range up to 10^{37} ergs/sec. A mediating accretion disk was proposed both by Avni and Goldman and later by Kriss et al. (1983). Such a disk could account for the observed spin up (Rappaport et al. 1978) during the 1978 outburst and the ~ 60 day delay between the optical and X-ray enhancements in 1980.

As was discussed in Chapter III, another potential source of material for the neutron star to accrete is the circumstellar envelope most Be stars are known to possess. Accretion of this material, which is strongly concentrated in the equatorial plane and has typical outflow velocities and densities of ~ 100 km/sec and 10^7 /cm^3, respectively, at a distance of 5×10^7 km (see van den Heuvel and Rappaport 1987 and references therein), would result in a persistent X-ray flux of $\leq 10^{35}$ ergs/sec. Furthermore, it can be shown that only unreasonable parameters for such an envelope, with several orders of magnitude change needed for both the material density or outflow velocity, could produce the 10^{38} ergs/sec observed during the 1974 outburst of 4U0115+63.

We are therefore led to consider the centrifugal inhibition of accretion model of Stella, White and Rosner (1986), hereafter SWR, using another Be star phenomenon, eruptive mass loss, as the mechanism which provides the material necessary to change accretion regimes and reproduce the observed X-ray luminosities. As we recall from Chapter III, the relative magnitudes of the radii involved, and therefore the accretion regime, are determined by the mass loss rate of the primary, $\dot{M}_*$, and the wind velocity, V_o. The critical parameter is

$$\gamma = \left(\frac{\dot{\mathrm{M}}_*}{10^{-8}\mathrm{M}_\odot \mathrm{yr}^{-1}}\right)\left(\frac{\mathrm{V_o}}{10^{8}\,\mathrm{cm\,s^{-1}}}\right)^{-4}$$

Using the observed and typical neutron star parameters for 4U0115+63, we find that the source will be in the X-ray dormant state (regime II) if gamma is ≤90. If an increase in mass loss rate, decrease in wind velocity or both increases gamma to a value of ~ 90–350, the source will overcome the centrifugal barrier and become X-ray active at an orbital phase centered on periastron. An increase in gamma to a value >350 will allow the pulsar to be active through all orbital phases.

In fact, using the typical envelope parameters mentioned before and given the measured magnetic field value of 1.2×10^{12} Gauss for 4U0115+63 (White, Swank and Holt 1983), it can be shown that indeed the source usually resides in regime II—i.e., $\mathrm{r_a} > \mathrm{r_m} > \mathrm{r_c}$. Thus little accretion actually takes place and, under "normal" conditions, a persistent low-level luminosity is not expected. However, the Be star phenomena of shell ejection and sudden eruptive equatorial mass loss can change gamma by several orders of magnitude and thereby change the accretion regime. Thus this model provides a natural explanation for the long dormant periods between events, the delay between the optical and X-ray increases, and the persistence of an optical enhancement after the X-ray emission has ceased.

Most X-ray sources considered "transient" do not exhibit the quasi-periodic recurrences apparent in the time history of 4U0115+63. The recurrence time of $\sim$ 3 years which can account for the five outbursts observed 1971–1987 is, however, consistent with the timescales seen in many Be star systems for a quasi-cyclic variation in the V/R intensity ratio. This ratio is defined as the ratio of violet-side to red-side peak intensities above the continuum in asymmetric double-peak emission lines. The radial motion of material superimposed upon rotation controls the value of the ratio. The line can be red or blue dominated depending on whether there is an inflow or outflow of material through the circumstellar line-emitting region. Cycles of 1–5 years are frequently seen in early-type Be stars and shell episodes are often correlated with these cycles (Dachs 1987). However, while there may be some correlation between the $\sim$ 3 year recurrence of an X-ray outburst and any enhanced mass loss associated with or embedded in the quasi-periodic V/R variation, the 180 day quasi-periodic recurrence time seen 1969–1971 is too short to be related to this particular phenomenon and must depend on some other type of Be behavior. Any model for these outbursts must also be capable of accounting for the maximum luminosity occurring at a phase of $\sim$ 0.5 in the five small outbursts seen to date. Perhaps the inflow time of material captured at periastron to move through a disk is ~ 0.5 cycle. It should be noted that the stronger outbursts of this source in August 1974, December 1980, and February 1987 do not appear to have the maximum intensities correlated with this orbital phase (Figure 4-6). This behavior is reminiscent of that seen in both V0332+53 and A0535+26.

Although the SWR model can account for many of the observed properties of 4U0115+63, one consequence of the model is that a source residing in regime II between outbursts should spin down via the "propeller" effect, as was seen between the 1978 and 1980 outbursts. However, we observe a $\dot{\mathrm{P}}$ of -4.4×10^{-4} sec between the 1971 and 1974 events. This observed spin up can be partially accounted for by accretion onto the neutron star during the 0.02 Crab year-long persistent emission observed 1971–1972 and the 25 days of outburst before the pulse period was detected in 1974. We can estimate the maximum possible spin up for these two states by using the disk-accretion equation for pulse period change as a function of luminosity given in Chapter III. The sum of the two effects produces a maximum pulse period change of -2.3×10^{-4} sec, which is still a factor of two lower than the observed value. This discrepancy can either reflect the large uncertainties in the accretion theory or else it must be possible for a source to spin up while in regime II and not accreting.

One mechanism, consistent with SWR, which may account for the possible spin up was suggested for the transient A0538-66 by Maraschi, Traversini, and Treves (1983). During the delay between the optical brightening and X-ray turn-on, when the material captured by the neutron star has still not reached the density necessary to start the accretion process, the material could accumulate at a rate faster than it can be propelled away. The result would be a

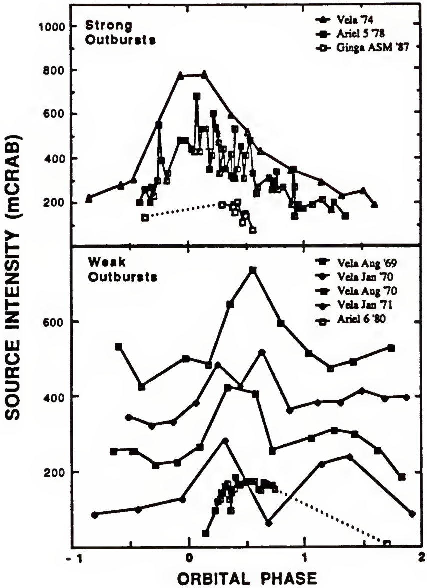

Figure 4-6. Time histories showing the low and high intensity outbursts as functions of binary phase. The weaker outbursts peak around phase 0.55, while the stronger events do not. Each Vela point represents a 4.6 day bins, except for the 1971 outburst which is shown in 9.3 day bins. Curves have been offset, bottom to top as follows: Upper panel: 0, 200, 200 mCrab. Lower panel: 0, 50, 200, 350, 450 mCrab. The 1987 outburst maximum was clearly missed during a data coverage gap (Tsunemi and Kitamoto 1988). Ariel 5 and Ariel 6 data are taken from Rose et al. 1979 and Ricketts et al 1981, respectively.

ring of material, outside the magnetospheric radius, which could spin up the neutron star while it is still in the inhibited accretion regime. This mechanism is discussed in detail by Wang (1979). The fast rise and slow decline seen in the light curve of the 1974 outburst is also consistent with the draining of such a reservoir. Thus, whether a spin up or spin down is observed between outbursts might depend on whether or not such a ring forms while the source is in its dormant state.

Summary

Observations by the Vela 5B X-ray satellite of 4U0115+63 during the years 1969–1979 show six transient outbursts. Two of these (January 1971 and December 1978) have been previously reported from observations by other satellites: four of the events—August 1969, January 1970, August 1970, and August 1974—are unique to the Vela data as it was the only X-ray astronomy satellite in operation at those times. The four small outbursts 1969–1971 occur $\sim$ 180 days apart and all reach a maximum intensity at an orbital phase of $\sim$ 0.5. A detection of a pulse period of 3.6142 seconds during the 1974 outburst, implies a spin up between the 1971 and 1974 events of -3×10^{-5} yr^{-1}. This is in contrast to the observed spin down between the 1978 and 1980 outbursts.

Including the 1974 outburst into the observational history of 4U0115+63, the transient is observed to be recurrent on a timescale of 3.0 $<$t $<$ 3.6 years since 1971. If this pattern persists, additional outbursts should have occurred between November 1983 and July 1984 and between October 1986 and June 1987. While no observations have been reported for 1983–1984, a detection of an outburst in progress at an intensity of 180 mCrab was recorded by the Ginga all-sky monitor upon start of operation in February 1987 (Tsunemi and

Kitamoto 1988) in agreement with this prediction. Continuance of this quasi-periodicity would lead to another outburst in 1990. Although the observation of the 180-day quasi-cycle is so far unique to the 1969–1971 Vela 5B data, recent observations of optical brightenings (Mendelson and Mazeh 1988; Henson and Imamura 1988) may suggest that this cycle is reappearing.

Centrifugal inhibition of accretion works well as a model for the Be star/neutron star binary 4U0115+63 in that it can account for the appearance of optical brightening before the X-rays, the continuance of the optical enhancement past the X-ray cutoff, and any spin down which has been observed to occur between X-ray outbursts. However, this model is dependent on some mechanism to force the binary from an inhibited regime into an accretion regime. In Be star/neutron star transients, this mechanism is most certainly the known Be star phenomenon of sudden equatorial mass loss. The evidence presented in this paper of a ~ 3 year recurrence time for a typical system like 4U0115+63 strengthens this conclusion in that eruptive mass loss from the Be star has also been observed to occur on quasi-periodic timescales of 1-5 years. This mass loss is correlated with the V/R ratio variation, which is representative of the inflow and outflow of material relative to the Be star.

V0332+53

Introduction

The first and, to date, the largest outburst of the X-ray transient V0332+53 was observed during the summer of 1973 by the Vela 5B satellite. To a limit of $\sim 5 \times 10^{-10}$ ergs/cm^{2}sec, the source was not seen to reappear until the Japanese Tenma satellite detected it in November 1983 (Tanaka et al. 1983). It was at this time that optical observations, based on the accurate source position determined from the EXOSAT low-energy telescope, led to the identification of the companion as a B star (Argyle 1983; Bernacca, Iijima, and Stagni 1983; Kodaira 1983). EXOSAT was pointed at the source several times between November 1983 and January 1984. The results were a detection of 3 small outbursts and a pulse period of 4.375 seconds. From this, a determination of the orbital elements was made including a binary period of 34.25 days and an eccentricity of 0.31 (Stella et al. 1985). It was seen that the three small outbursts were centered on periastron passage. The appearance of regular pulsations along with large amplitude flux variability on timescales from milliseconds to hours caused this source to be initially classified as an unique type of X-ray object. Stella, White, and Rosner (1986) then used the behavior of this source to suggest centrifugal inhibition of accretion as a physical model for Population I binary transients. The results presented here are from a reanalysis of the July-September 1973 outburst using the Vela 5B data with a finer time resolution than used by Terrell and Priedhorsky (1984), hereafter TP.

Observations

The ten year time history of V0332+53 is shown in Figure 4-7. Immediately obvious is the fact that the 1973 event is the only appearance of this source to a level of $> 6 \times 10^{-10}$ ergs/cm^{2}sec (0.02 Crab) during the interval June 1969 – June 1979. Figure 4-8 is a close up of the 1973 event. The light curve, while generally symmetric, has a great deal of short timescale structure. This is in large part due to strong variability on the order of minutes within the $\sim$ 4–10 hr observation sequences of the source by the satellite.

The outburst lasted from $\sim$ 30 May to $\sim$ 2 September, 1973. An average maximum intensity of 1.6 Crab (on 56-hr averages) was reached on $\sim$ 10 July.

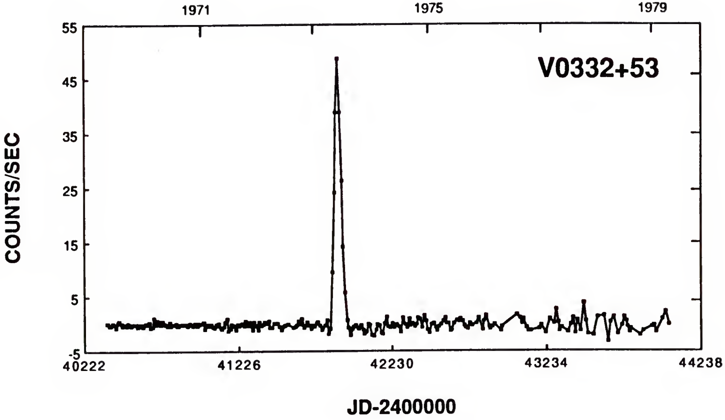

Figure 4-7. Time history of V0332+53 1 June 1969–9 June 1979 (JD2440373–JD2444033) as seen by Vela 5B in the 3–12 keV energy channel. Each point represents a 9.33 day average (2 satellite orbits).

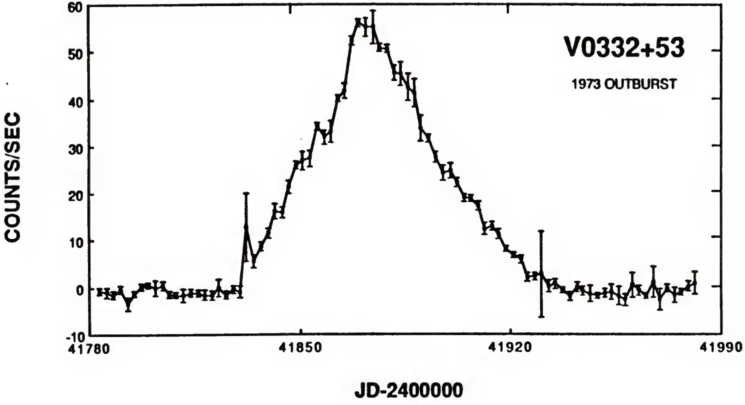

Figure 4-8. Time history of the 1973 outburst. Shown are data from 12 April–26 October (JD2441783–JD2441982). Each point represents the average of a single satellite observation sequence in the 3–12 keV channel. These sequences recur every 56 hours.

Large variations (factors of 2–4 on 1-sec timescales) were seen throughout the outburst, frequently attaining values of ~2.5 Crab. A value of 1.6 Crab corresponds to a luminosity of $3.2 \times 10^{36}(D^2)$ ergs/sec, where D is the distance to the source in kpc. Distances from 1.5–5.0 kpc have been suggested for V0332+53 (Stella et al. 1985; Corbet, Charles, and van der Klis 1986). A precursor occurring approximately 30 days before the outburst, as was reported by TP, is no longer apparent. This is due to a slight error in the source location assumed for that analysis. TP used a position derived from the Vela 5B data; here, the more accurate EXOSAT position is used.

The outburst was extremely hard, with the average hardness ratio (6–12 keV/3–6 keV) during the period 19 June–28 August being 1.19 ± 0.01. Such a value is typical of Be/neutron star binaries (Rappaport and van den Heuvel 1982). For comparison, the average value for the Crab at this time is 0.593 ± 0.008. The suggestion by TP of a slight softening near outburst maximum is not seen to be a significant when the data are looked at on 56-hr timescales rather than 10-day averages. Their apparent softening is the result of random sampling of large variations in the hardness ratio on timescales of seconds to minutes. Values of the hardness ratio are seen to range from 0.6 ± 0.2 to 1.9 ± 0.1 during a single observation sequence and this behavior persists for the ~ 80 days that the source is visible in both of the Vela 5B energy channels (Figure 4-9). No correlation of hardness with the large changes in source intensity is observed.

The known 4.375 sec pulsar period is detectable at a statistically significant level during two observational sequences of the outburst–first on 3 July and then again on 31 July. The average source luminosity was 2.8×10^{36} (D^2) and

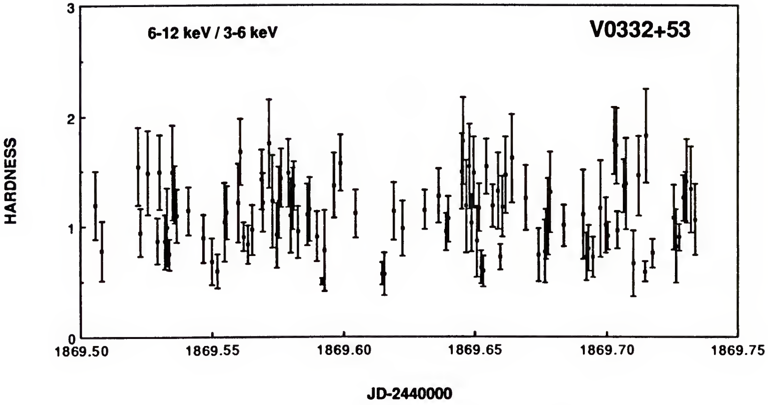

Figure 4-9. Typical time history of the hardness ratio variations during a 6 hr observation sequence on 5 July 1973. Each point represents a 1-s data accumulation.

1.6×10^{36} (D^2) ergs/sec, respectively, on those dates and the periods seen are 4.3751 ± 0.0001 and 4.3748 ± 0.0001 secs. The data from each sequence are folded on its respective period and shown in Figure 4-10. The formal probability of finding a random peak in the epoch folds in the frequency range searched (4.37–4.38 secs), in the observation sequences searched, with a χ^2 equal to that seen is $\sim 6 \times 10^{-4}$. Lack of a detection of the pulsations during any of the other observation sequences is due to poor data coverage by Vela 5B and is not necessarily due to their disappearance or a reduction of the pulsation amplitude. In both of the pulsation detections, there is a ~ 30% peak-to-peak variation. This is a factor of two greater than what was seen by EXOSAT in the weak 1983 outbursts. The detection of this pulse period implies a secular spin down of $< 4 \times 10^{-13}$ sec^{-1} over the epoch 1973–1983.

When a general trend is subtracted from the outburst light curve, a discrete Fourier transform of the residual time history of the outburst reveals a 33.8 ± 2.3 day modulation, consistent with the known binary period (Stella et al. 1985). The trend used for the analysis was a Gaussian; similar results, however, were obtained using a triangular fit or a combination of power law fits to the rise and decline. The probability of finding so large a peak randomly in the transform at this known period in the data is $\sim 7 \times 10^{-5}$. The outburst fit and the fit subtracted light curve is shown in Figure 4-11. This effect was hidden in the 10-day averages used by TP.

Pulse timing analysis to improve the determination of the orbital elements is not possible with the Vela 5B data on V0332+53 due to poor statistics. However, an orbital period of either 34.38 ± 0.02 or 34.07 ± 0.02 days and a time of

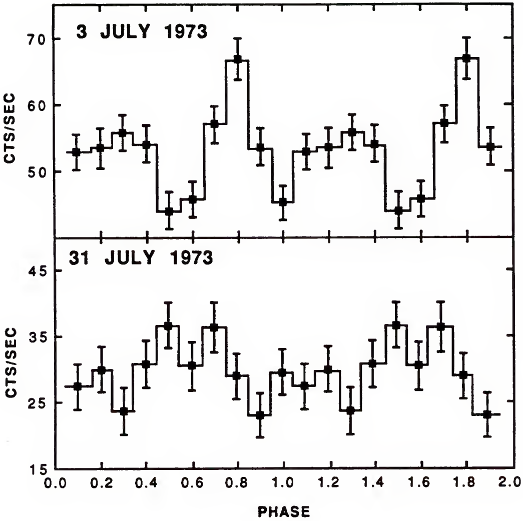

Figure 4-10. The average pulse profile of V0332+53 in the 3–12 keV channel. The top frame is data from 3 July 1973 folded modulo the best fit period of 4.3751 seconds; the bottom frame represents data from 31 July 1973 folded modulo the best fit period of 4.3748 seconds. Phase zero is arbitrary.

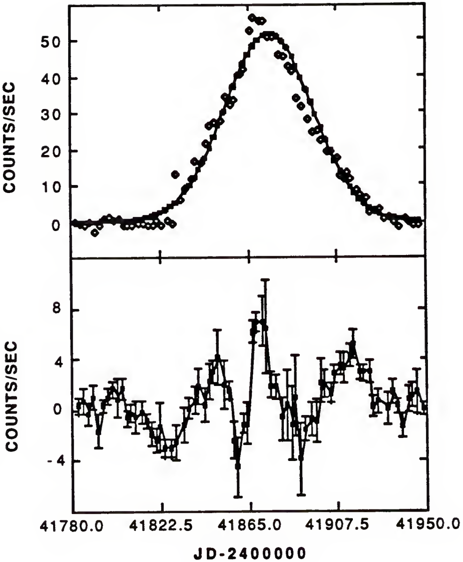

Figure 4-11. Resulting time history of the 1973 outburst after a trend is removed. Shown are data from 12 April–23 September (JD2441783-JD2441949). Each point represents the average of a single satellite observation sequence in the 3–12 keV channel. Upper panel shows the Gaussian fit; Lower panel shows the fit-removed data with 34 day orbital modulation readily apparent.

periastron passage of JD 2441870.00 ± 1.0 JD can be suggested if a maximum X-ray flux at periastron is assumed. This is accomplished by combining the Vela 5B values for periastron passage and observed orbital period with the corresponding values determined from the 1983 observations and iterating for the smallest residual of either 110 or 111 orbital cycles, respectively. Any $\dot{P}$ is ignored in this analysis. These values imply periastron on JD 2445651.76 ± 1.0 for the EXOSAT data–consistent with their quoted value of JD 2445652. ± 1. The greater of the two suggested orbital periods is the more likely, however, neither of the two can be ruled out with 3σ confidence at this time.

Discussion

The 1973 outburst of V0332+53 was originally analyzed by TP using the Vela 5B data in 10-day averages. A reanalysis of this data, with the intrinsic 1-second resolution of the data restored, both confirms that this was indeed the source V0332+53 and reveals some new and some different results. Now present is a detection of the pulse period during the 1973 event which implies a secular $\dot{P}/P$ of $< 4 \times 10^{-13}$ sec^{-1} between this outburst and the next detection of the source ten years later. Furthermore, an orbital modulation of the X-ray flux is seen to be superposed on the overall outburst envelope. The new analysis also shows that significant variations in the hardness ratio exist on timescales of seconds to minutes. These variations are uncorrelated with the large intensity variations on similar timescales. Random sampling of this effect caused the slight softening near outburst maximum seen by TP. Finally, use of the more accurate EXOSAT source position removes any evidence of a precursor from the light curve of the source. In light of these new results, models for this binary transient will be reexamined.

We recall from Chapter III that Stella, White, and Rosner (1986), hereafter SWR, used V0332+53 as their example source in a paper concerning intermittent wind accretion due to the centrifugal inhibition of accretion in Population I binaries considered "transient". Using the observed and typical Be/neutron star parameters for V0332+53 ($\mu = 10^{30}$ G cm^3, $M_* = 10M_\odot$), the source will be in the X-ray dormant state (regime II) if γ is ≤ 85 . If an increase in mass loss rate, decrease in wind velocity or both increases γ to a value of $\sim$ 85–310, the source will overcome the centrifugal barrier and become X-ray active at an orbital phase centered on periastron. Any further increase in γ will allow the neutron star to be active through all orbital phases. Thus there is a natural explanation for the two distinct types of outburst behavior observed. In a low γ outburst, accretion is sharply modulated on the orbital cycle such as was observed by Tenma and EXOSAT; in a high γ outburst such as that in 1973, accretion will persist throughout the orbital cycle.

The primary justification for using V0332+53 as the example in the SWR paper was the fact that the source was known to have exhibited both outbursts which recur periodically at periastron and a large outburst which occurred at a random orbital phase. In the case of V0332+53, the 1973 outburst is the only example of this latter type of outburst to date and was thought to exhibit no orbital modulation in the light curve. Orbital modulation would be expected if the increased X-ray emission is due to accretion of the denser Be star shell material or envelope expected near periastron. The present analysis shows that in fact there was indeed an orbital modulation present in the 1973 outburst. Furthermore, a simple model based on the Be star phenomenon of shell emission or an evolving circumstellar envelope is consistent with the optical observations of enhanced brightness around/before the X-ray outbursts in 1983 and the cessation of X-ray activity with the disappearance of Hα emission at subsequent times (Corbet, Charles, and van der Klis 1986).

The pulse period of V0332+53 detected in the 1973 event implies a secular change of $\dot{P}/P$ of $< 4 \times 10^{-13}$ sec^{-1} over the epoch 1973–1983. This result assumes that an outburst did not occur between mid-1979 and late-1983. It is possible that one did occur and was missed by the sporadic sky-coverage generally available during that timeframe. The organization and analysis of the P78-1 satellite data could resolve the issue. This value is comparable to the upper limit on any spin down seen by EXOSAT during the $\sim$ 30 days between the small outbursts in 1983 ($\dot{P} \leq 3 \times 10^{-12}$ sec/sec). Combining the implications of such a low value with the fact that the source was not detected above a threshold of $\sim 5 \times 10^{-10}$ ergs/cm^{2}sec during the subsequent six years of Vela 5B all-sky monitoring, it is obvious that the optical companion must have gone through an extended period of quiescence. If the source was in an inhibited accretion regime, there must not have been enough material in the surrounding area to spin down the pulsar via the "propeller" effect. If the outbursts are due to enhanced accretion from an evolving stellar envelope, the envelope must have been of negligible density for this ten year period. Such long quiescent periods have been seen for several early-B stars (Dachs 1987).

Summary

Observations of the X-ray transient V0332+53 by the Vela 5B satellite show only one outburst during the epoch June 1969–June 1979 above a level of 0.02 Crab. This event occurred during June–September 1973 and reached an average maximum flux of 1.6 Crab. There were large (factors of 2-4) variations on 1-sec timescales reaching values up to 2.5 Crab throughout the outburst. The known pulse period was detected during two different observational sequences, with values of 4.3751 ± 0.0001 and 4.3748 ± 0.0001 secs. This implies a secular $\dot{P}/P$ of $< 4 \times 10^{-13}$ sec^{-1} between this event and the next observed outburst in November 1983. A modulation at the known 34–day orbital period of this system is present in the 1973 event after a general trend is fitted and removed from the data. The random chance of this peak in the Fourier transform occurring at the expected frequency is $\sim 7 \times 10^{-5}$. This modulation can be used to suggest an improved orbital period of either 34.38 ± 0.02 or 34.07 ± 0.02 days.

GX301-2 (4U1223-62)

Introduction

The X-ray source GX301-2 (4U1223-62) was found to exhibit regular, double-peaked X-ray pulsations with an $\sim$ 700 sec period (White et al. 1976). Based on a pulse timing analysis of the Ariel 5 data, White, Mason, and Sanford (1978) suggested a 40.8 day binary period for the source. Thereafter, other researchers reported orbital periods of 32.5, 35.0, and, finally, 41.5 days (Kelley et al. 1980; Watson et al. 1982; Priedhorsky and Terrell 1983; Sato et al. 1986). This latter value—determined from Ariel 5 SSI, Vela 5B and a combination of Ariel 5, SAS 3, Hakucho and Tenma data—is now accepted to be correct. Other orbital elements for this system include an eccentricity of 0.47 and a zero epoch of JD 2,443,906.56 (Sato et al. 1986). Outbursts recur regularly at the orbital period, typically lasting for 1–9 days and consistently occurring $\sim$ 1.5 days prior to periastron passage (Warwick, Watson, and Sims 1981). Large variations in the X-ray flux on timescales of minutes to days have also been observed (White, Mason and Sanford 1978). Several factors contributed to the trouble in establishing the correct binary period: 1.) The optical counterpart, the B supergiant WRA 977, exhibits a light modulation with a 22.6 day period (Vidal 1973; Bradt et al. 1977; Pakull 1978) with no apparent modulation at 41.5 days, 2.) the amplitude of the 700 sec pulsations is highly variable—at times as high as 60% and at other times undetectable (Mitani et al. 1984) and 3.) the pulse period displays one of the largest variations (ranging from 696 to 701 sec over 10 years) of any similar binary transient (Sato et al. 1986).

Simple stellar wind accretion models can successfully predict the overall binary phase dependence of the X-ray flux. However, such models cannot account for the short duration of the X-ray outbursts nor the occurrence of the centroid of these events before periastron. As a result, it was suggested that the wind velocity profile of the primary must somehow be modified to account for the orbital light curve (Rothschild and Soong 1987). This concept must then be added to those suggested to model the pulsation profiles, namely, that of a two-component model where there is a pulsating, highly variable component and a non-pulsating, roughly constant component (Mitani et al. 1984). Neither of these concepts, however, can successfully account for the large pulse period changes observed for this source and so another component to such a 'combination model' would be necesssary. The large spin ups and downs observed in GX301-2 are believed to be due to either (1) fluctuations in the angular momentum transfer to the neutron star, (2) fluctuations in the coupling between different components in the neutron star interior, or (3) fluctuations in the moment of inertia of the neutron star. The second possibility is ruled out from consideration of the timescales involved in the spin period changes versus those involved in internal neutron star mechanics (Lamb et al. 1985). The third possibility is ruled out by both the large magnitudes of the spin period changes and the reversal of sign of the changes. Thus we are led to search for some mechanism which might provide large changes to the angular momentum transfer rate to the neutron star.

Observations

Three other known X-ray sources are near enough to GX301-2 ($< 6°$) to provide some source confusion to the light curve, depending on the satellite scan direction. Fortunately, all three of these sources, 4U1145-619, Cen X-3, and GX304-1, have known X-ray periodicities which can be searched for in the GX301-2 data as a measure of their contributions to the observed flux. None were seen. In fact, except for the strong 1973 outburst of 4U1145-619, these sources serve only to contribute a small (<1.5 cts/sec) constant to the GX301-2 data, which is easily removed. A further check was done by comparing the data in 10-day averages to that of Priedhorsky and Terrell (1983), on which the intensities of the four sources had been deconvoluted. The match was excellent. Thus, in the analyses done here, only the April 1973 data dominated by 4U1145-619 have been deleted from the data set.

The ten year time history of GX301-2 is shown in Figure 4-12. The outbursts or flares associated with periastron passage are apparent in this 10-day average plot only when they are unusually strong or long (i.e. maximum average intensity $\geq$ 0.15 Crab, lifetime $\geq$ 2.5 days). With finer binning, however, the 41 day recurrence time is easily observable as are the differences in shape and duration of the flares (Figure 4-13). This modulation, assumed to represent the binary period, can be tracked through most of the 10-year Vela 5B lifetime. The

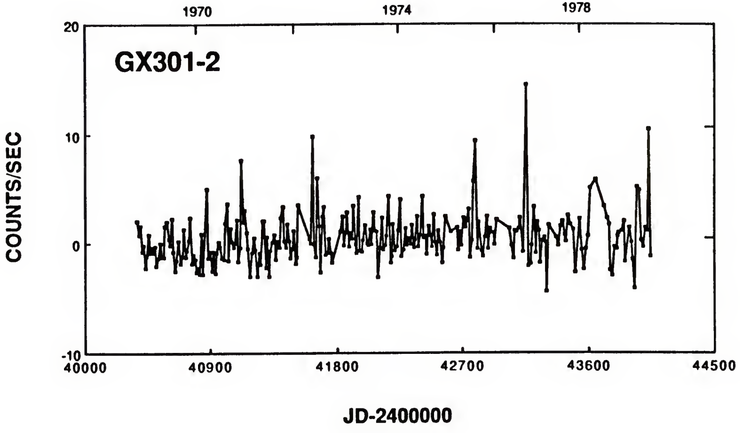

Figure 4-12. Time history of GX301-2 1 June 1969-9 June 1979 (JD2440373-JD2444033) as seen by Vela 5B in the 3–12 keV energy channel. Each point represents a 9.33 day average (2 satellite orbits).

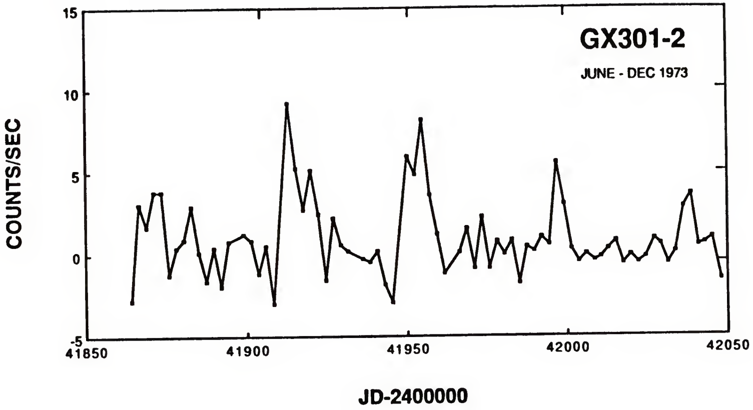

Figure 4-13. Time history of GX301-2 28 June 73–30 December 73 (JD2441850–JD2442050) as seen by the Vela 5B satellite in the 3–12 keV energy channel. Each point represents a 56 hour average. Clearly apparent are the 41-day flares and the variabilities in amplitude and lifetimes of these events.

exception is a stretch of time in 1977 when the flares occur during data coverage gaps for the source. In general, these flares reach average intensities (on 56-hr timescales) of 0.10–0.40 Crab and last from ~ 1–9 days. These values are consistent with previously reported observations (Warwick, Watson, and Sims 1981). The values 0.01–0.40 Crab correspond to values of 6.1×10^{35}–2.8×10^{36} ergs/sec at a distance of 1.8 kpc (Parkes et al. 1980). Folds of the data on the 41.5 day period are shown in Figure 4-14. The scatter in phase of the times of maximum X-ray emission relative to the periastron epoch is shown in Figure 4-15. This epoch, JD 2,443,906.56 ± 0.16, was derived by Sato et al. (1986) from a joint pulse arrival timing analysis of data from four different satellites. The preference for maximum intensity to be reached at an orbital phase slightly before periastron is obvious. However, it is also seen that there are times when the maximum is reached at phases at or after periastron. The resolution of each of the observations is 2 days or 0.05 binary phase and, therefore, slight adjustments of the period cannot account for the 0.8–1.1 spread of phases seen. No correlation in the shifts of the occurrence of X-ray maximum with orbital phase is seen, although it appears that only prior to 1975 did flares occur which reached their peak intensities after periastron. However, it is clear from Figure 4-15 that Vela 5B does not have as good of a coverage of the source after that time. Thus, this may be just a selection effect.

Ricker et al. (1973) reported balloon experiment observations made 15-16 October 1970. Extrapolating back from their 15-50 keV observations to lower energies using the acceptable fit of either a simple exponential or power law spectrum ($e^{-E/kT}$ where kT = 6 keV or $E^{-\alpha}$ where $\alpha = 5$) implied an intensity of ~ 10 Crab in the 1-10 keV energy range, unless there was some

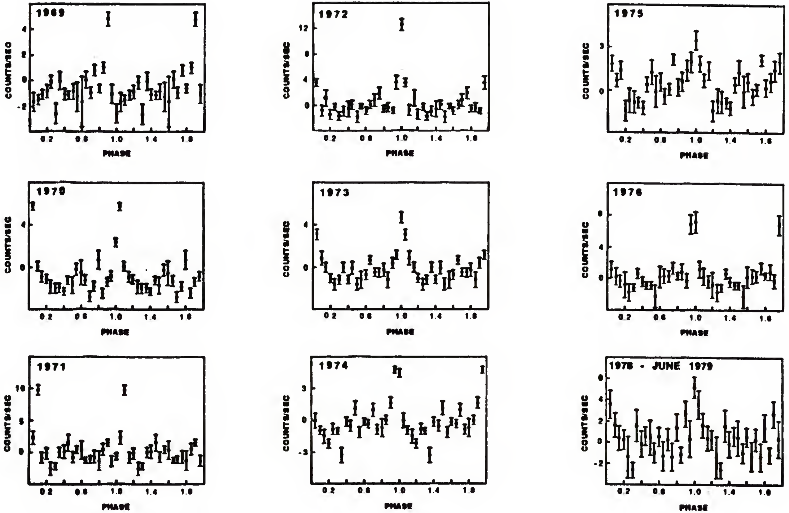

Figure 4-14. Folds on the 41.50 ± 0.05 day orbital period of GX301-2. Recurrence of the short-lived x-ray flares around periastron (JD2443906.56) is evident. Each bin shown represents ~2 days.

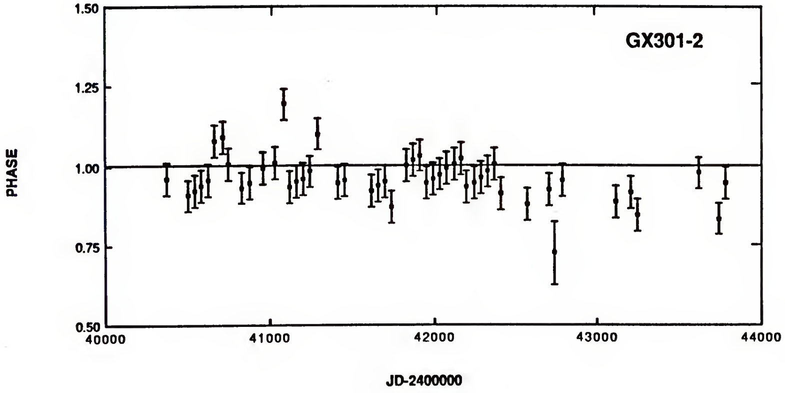

Figure 4-15. Relation of the maximum intensities seen in the 3-12 keV channel for each of the x-ray flares to periastron passage (Sato et al. 1986). While the preference is for an orbital phase before periastron, a significant number of events occur at or after phase zero.

type of low energy cutoff. Vela 5B observed the source 10-14 hours before the balloon observations. The average intensity was 0.07 Crab, with variations up to 1.1 Crab during the observation sequence typically lasting about 20 minutes. On the next data sequence for this source, 2.3 days later, the average intensity was $\sim$ 0.3 Crab, again with variations up to 1.4 Crab on timescales of tens of minutes. Clearly these values are substantially below the 10 Crab value extrapolated from the high-energy balloon observations. It should be noted that the γ-ray observations were made $\sim$ 2 days before periastron passage, a time now known to be the focus of the enhanced low-energy X-ray emission and, perhaps, even stronger activity at higher energies.

The average hardness ratio (6-12 keV/3-6 keV) for GX301-2 is seen to be 1.39 ± 0.07 for the flares over the ten year period. Such a high value is typical of the massive binaries. The large statistical errors due to the low average count rates makes it difficult to observe a correlation between the hardness ratio and source intensity, such as was seen in the Hakucho data by Mitani et al. (1984). The average hardness ratio seen here is consistent, however, with those observations of similar intensity seen in the Hakucho data.

The pulsations, highly variable in both period and amplitude, are apparent at a statistically significant level on four occasions over the ten year period 1969-1979 in the Vela 5B data. The results from the 3-12 keV energy channel, shown in Figure 4-16, add several new points to the long-term curve of pulse period versus time. In fact, three of these observations are prior to any of the previously published results which start in January 1975. Pulse periods of 704.5 ± 2.2, 696.9 ± 2.2, 693.8 ± 1.7 and 691.7 ± 1.7 seconds are observed on 16 October 1970, 23 January 1973, 26 April 1974 and 26 December 1975, respectively. The

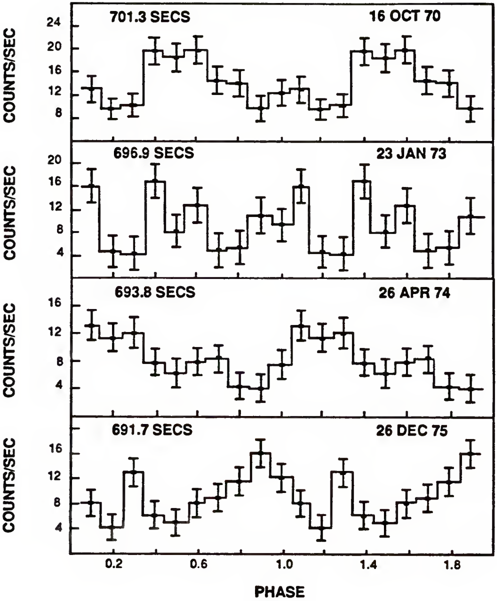

Figure 4-16. Folds on data sequences shown with the respective pulse periods for the four different times. Phase zero is arbitrary for each. Note the large variability in both period and shape, although there is, generally, a double peak structure.

peak-to-peak amplitudes of the pulsations are 50 ± 15%, 68 ± 25%, 69 ± 30%, and 75 ± 15%, respectively. The value of 693.8 ± 1.7 seconds seen in December 1975 is within 2σ of the values of 695.7 ± 0.15 seconds detected by OSO-8 in early January 1976 (Swank et al. 1976) and the value of 696.8 ± 1.5 seconds observed in the Ariel 5 data in early December 1975 (White et al. 1976). The formal probabilities of finding random peaks in the folds with χ^2 values equal to those observed for the four observation sequences used all lie in the range $3-7\times10^{-3}$. The large errors associated with each value are due to the lengths of the various individual observation sequences. Two adjacent observation sequences could not be folded together, thus improving the error, because of the short durations and low average count rates involved. Nor was it possible to combine the data from different periastron passages since the $\dot{P}$s over the 41.5 day intervals have been measured to be significant (values up to 0.5 sec—Sato et al. 1986). There were fourteen other observation sequences in the Vela 5B data, based on the average count rate and number of observations in the sequence, when a detection of the pulse period was expected and no modulation was found to a level greater than 10%. Dates for these non-detection observation sequences are listed in Table 4-2. Such disappearances or reductions in the amplitude of the modulation are well known, however (Mitani et al. 1984).

Discussion

GX301-2 is an X-ray binary with a B2I star as the primary. It is one of seven systems known to have a supergiant companion and, by far, has the longest orbital period and highest eccentricity of any of them. The closest value to the 41.5 day period is the 9.0 day period of Vela X-1; the closest value to the eccentricity of 0.47 is also that of Vela X-1, namely 0.09. Thus, GX301-2

TABLE 4-2

Observations with No Pulsation Detection

5 June 1969
8 January 1971
31 October 1972
12 December 1972
1 October 1973
10 November 1973
17 July 1974
8 October 1974
31 December 1974
20 March 1975
15 October 1975
9 January 1976
3 December 1976
17 April 1978

is clearly unusual even among other high-mass binary systems. As discussed in detail by White (1985), to account for the observed persistent X-ray luminosity of $\sim 10^{36}$ ergs/sec and the periodic outbursts just before periastron passage with $\sim 10^{37}$ ergs/sec, a mass loss rate of $\sim 7 \times 10^{-5}\ M_{\odot}$/yr is required. This is close to the maximum possible value if it is assumed that all of the momentum of the primary's radiation field is transferred to the wind. Another possibility to account for the observed luminosity, as was discussed in Chapter III, is a reduction of the natural wind velocity. In the case of a supergiant system like GX301-2, the wind velocity can be reduced due to the X-ray "feedback" mechanism as discussed and modeled by Ho and Arons (1987). However, using the barest version of the model, the high luminosity solution to the equations yields X-ray luminosities which are 100 times Eddington and 1000 times the observed values (Ho, private communication 1987). It thus appears that the simplifying assumptions used in those calculations must be examined to see if they might no longer apply to a supergiant binary with appreciable orbital eccentricity, such as is the case for GX301-2. As given in Chapter III, the assumptions made were 1.) corotation of the wind, such that there is only radial motion in the frame corotating with the primary, 2.) no effects from the X-ray heating of the incoming wind material, and 3.) no effects from the X-ray radiation pressure. Assumption 1 was made in order to ignore any Coriolis or azimuthal forces. Inclusion of the effects of the Coriolis force was tested and seen to cause insignificant changes to the resulting X-ray luminosities. Assumption 2 was made to ignore any pressure gradients against the wind or changes induced in the sound speed. Inclusion of these effects, again, does not significantly alter the results. Assumption 3 was made so as to be able to have a constant secondary mass. In an optically thin wind, inclusion of this effect would modify the effective neutron star mass by a factor related to the Eddington luminosity. This would then leave us with no steady-state luminosity solutions with values greater than the Eddington luminosity and greatly reduces the number of overall solutions to the equations. In the case of GX301-2, the only solution left, in fact, is the lowest luminosity one which is far below the observed value. The one possibility remaining for this model to successfully account for GX301-2 is the introduction of a finite amount of transverse wind velocity resulting from the lack of perfect corotation. However, this would introduce a new parameter into the equations and such a modification is left for future work. Regardless of the potential problem in accounting for the luminosity, it is also unclear how this simple model alone can explain the large spin period changes of the neutron star. In a subsequent paper, Ho and Arons (1987b) showed that for the low-luminosity solution it was possible to have temporary accretion disk formation around the neutron star, depending on the angular momentum dissipation mechanism. In such a way it might be possible to explain the spin ups and downs of sources like Vela X-1. However it remains unclear as to whether or not such a mechanism is applicable to those sources which are accounted for by any other of the luminosity solutions.

The possibility of investigating the hydrodynamics of the accretion flows in wind-fed binaries has become available due to high-speed computers. Taam and Fryxell (1988) have recently simulated accretion for an inhomogeneous wind past a finite-sized gravitating object. The neutron star need no longer be considered a point source; the wind need no longer be perfectly symmetric. Their results show that the flow is highly time-dependent, with the temporal behavior of shocks in the flow varying the mass accretion rate onto the neutron star by more than an order of magnitude. Furthermore, and in the case of GX301-2 perhaps most importantly, it was shown that under such circumstances, accretion disks can form on timescales much shorter than the orbital period and can possess either rotation sense. Thus, this model appears to be capable of accounting for both the observed X-ray luminosity and the large short-term changes in the pulse period of GX301-2. Caution must be exercised here, however. At present, this model is confined to two-dimensions and the disruption of the flow patterns due to effects from the third-dimension are not yet clear. This work is currently in progress by Fryxell and Taam (1988).

Summary

The B2 supergiant/neutron star binary GX301-2 (4U1223-62) was observed by the Vela 5B all-sky monitor from June 1969 - June 1979. Clearly evident is the 41 day flare cycle, presumably the binary orbital period for the system. The strengths and lifetimes of these events are highly variable—ranging from 0.09 Crab to 0.4 Crab and from less than 2 days to 9 days. The $\sim$ 700 second pulsations, known to be extremely variable in both amplitude and period, exhibit this behavior over all ten years of Vela 5B observations. Values from 691 - 704 secs are observed in four different observation sequences, with no apparent modulation (to a level of 10 %) observed for fourteen other sequences during which a detection was expected. The new model of Taam and Fryxell may at last provide some insight into the exotic temporal behavior of this binary.

CHAPTER V
SUMMARY AND CONCLUSIONS

The origin of the material which accretes onto a neutron star and produces X-rays was originally divided into two classes: stellar wind and Roche-lobe overflow. As observations began to show that there was a major class of X-ray sources, the transients, which often consisted of either a B or Be/neutron star binary, it was realized that the mass exchange between these particular stars was not due to either of the standard, simple mechanisms. In the B star binaries , the winds are believed to be responsible for the material which is accreted by the compact companion; in the Be star binaries, the known eruptive behavior of the Be star is believed to supply the necessary material. The latter type stars are known to exhibit two distinct types of phenomena which can provide enough matter for the neutron star to accrete and produce the observed X-ray fluxes and light curves. Namely, the possession of an evolving circumstellar envelope and sudden equatorial mass ejection. Using the Vela 5B all-sky X-ray monitor over the epoch June 1969–June 1979, an attempt was made to analyze the long-term behaviors of three massive binaries, 4U0115+63, V0332+53, and GX301-2, and understand any similarities or differences between these systems. As a result of the analyses, current theoretical models could also be tested.

Several discoveries were made during the course of this work. Four previously unknown outbursts by 4U0115+63 were discovered, establishing a quasi-periodic recurrence time for that source of $\sim$ 180-days which appears to have been replaced subsequently by a $\sim$ 3-year recurrence cycle. An in-depth analysis of the major outburst in August 1974 produced a detection of the pulse period of 3.6142 secs. This implies a spin up of $\sim -3 \times 10^{-5}$ yr^{-1} between the 1971 and 1974 events. Observation of a spin up is in direct contrast to the spin downs observed between subsequent outbursts. Also, a trend was seen for the weaker outbursts of this source to occur at apastron. There was only one outburst of V0332+53 in the Vela 5B data base. This occurred in the summer of 1973 and had been previously analyzed in 10-day averages by Terrell and Priedhorsky (1984). However, a reanalysis on finer timescales produced some new and different results. For example, the suggested precursor event proved to be due to a slight source location error; the suggestion of a spectral softening near maximum luminosity was due to the 10-day averages randomly sampling large variations in the hardness ratio on timescales of seconds to minutes. These variations do not appear to be correlated with the large intensity changes also seen on similar timescales. Two detections of the pulse period during the outburst imply a secular change of $\dot{P}/P$ of $< 4 \times 10^{-13}$ sec^{-1} between 1973 and the next detection of the source in November 1983 by the Tenma satellite and EXOSAT Observatory. Finally, an orbital modulation appeared superposed on the outburst light curve and allowed an improved orbital period of either 34.38 $\pm$ 0.02 or 34.07 $\pm$ 0.02 days to be determined. The B supergiant/neutron star binary GX301-2 was known to have a 41.5 day orbital period with flares occurring 1-3 days before periastron and lasting 1-9 days. The long lifetime of continual coverage by Vela 5B allowed this periodicity to be tracked for 10 years. It was seen that indeed the flares lasted from 1-9 days, possessed amplitudes from 0.15 Crab to 0.35 Crab on 56-hr averages (with 1-sec variations in those averages up to 2 Crab) and reached maximum intensity at orbital phases 0.8–1.1 during the epoch 1969–1979. The pulse period, known to change by 0.5 secs in less than an orbital period, was seen to exhibit obviously large $\dot{P}$ values at times prior to all of the previously published detections. Furthermore, even adding detections of the pulsations from 1970, 1973, and 1974 into the timeline so that now over eighteen years are covered, no secular spin up or spin down trend emerges.

It is clear that both the Be phenomena of circumstellar envelopes and sudden equatorial mass ejections play an important role in the X-ray histories of two of the three binaries investigated. In the case of 4U0115+63, the stronger outbursts which recur on quasi-periodic timescales of 3 years are most certainly related to the mass outflow measured optically by the V/R ratio. This ratio also exhibits cycles in the 3-5 year range for early-B stars. On the other hand, the weaker 180-day recurrences seen 1969-1971 are most probably due to an evolving circumstellar envelope which could have been present around the star at that time. The observed X-ray fluxes can be handily explained by densities and outflow velocities typical of those that have been inferred from measurements of other Be stars. The source V0332+53 also exhibits outbursts due to both phenomena, with the 1973 event possibly being a combination of the two. This concept can explain both the large maximum X-ray luminosity seen as well as the orbital modulation superposed on the overall outburst light curve. Ten years later, when Tenma and EXOSAT observed a recurrence of this source at a low level, with X-ray flux centered on periastron and correlated to the appearance of Hα in the optical spectrum, a circumstellar envelope was clearly present and was the source of accretion material.

The behavior of GX301-2, in contrast, is apparently dominated by the movement of the neutron star deeper and deeper into the surrounding envelope of its B supergiant optical companion. Nonetheless, the previously reported preference of X-ray activity for a binary phase slightly before periastron remains somewhat of a mystery. The long-term observations discussed here, however, show a significant scatter in this correlation over a ten-year period. The spin ups and downs of this system are seen to have been occurring at times prior to previously reported observations, leading to the result that there is still no apparent secular change in the spin period with twenty years of data. The short term variations in the pulse period as well as the overall X-ray luminosity may be the result of a non-axisymmetric wind flow past a finite-sized neutron star, however, and this model is currently under development by other researchers.

Clearly, long-term observations with an X-ray all-sky monitor are needed in order to pursue the understanding of the massive binary systems. In many cases these systems do not recur for timescales of decades, thus a commitment of great patience is necessary. Simultaneously, an optical observation effort to monitor the companions for corresponding changes would be required to clarify the true relation of the stars and their activities. At this point, with twenty years of fairly good coverage of the X-ray sky, the long timescales necessary in order to accumulate enough events or outbursts of the massive binary "transients" leave us still with only hints at the physical processes occurring in these systems. In many ways, the various sources exhibit similar behavior—either persistently or temporarily revealing periodic recurrences and displaying X-ray modulations and intensities which apparently require different physical processes to be responsible for individual recurrences. And yet, these same similarities are present on such different levels in the various sources as to imply some fundamental difference. It, thus, remains questionable whether these sources exhibit variations on a common, underlying—and as yet unknown—theme or else truly represent several unique processes. Only in the latter case can we justify separate X-ray source classifications (e.g., classical transients, recurrent transients, and highly variable sources) and only continued, improved observations can provide the tools to solve this problem.

APPENDIX A
COMPUTER PROGRAM INFORMATION

During execution of the NOS-to-VMS conversion program, various problems were encountered. One of these was a spin period of 0.0 secs entering the data stream for a second or two at random times on several of the 36 tapes. This did not occur often and was handled by setting SPINP = 99.9999, if SPINP = 0.0 was read from tape. The result of this usually caused that spin of data to be rejected. However, even if it made it through to the output tape, the unusual and unreal value of the spin period would flag it for the VAX program.

A clever procedure file was written (with the invaluable assistance of Bob Ayars, Los Alamos CDC Consultant) to automatically request the mounting of each input and output tape, as well as to automatically restart the program code for each input tape. This proved to be a great help, in that continual monitoring of the program was unnecessary.

The procedure file for running program the NOS-to-VMS conversion program is listed below. This file would process the time-ordered input tapes P02104,P01885,P01902,P01871, P01810,P01000 in sequential order and write the VAX-readable output to tapes LAW1, LAW2, etc.

```
/JOB
SKY.
/USER
NORERUN.
SETASL,*.
```

```
SETJSL,*.
SETTL,*.
RESOURC,GE=1,PE=1.
COPYBR,INPUT,SKYLOOP.
GET,INPUT=IN.
ATTACH,SKYC.
FILE,TAPE10,RT=F,MRL=6720,BT=K.
VSN,TAPE10=LAW23/LAW24/LAW25/LAW26/LAW27/LAW28.
LABEL,TAPE10,D=GE,F=L,LB=KU,PO=W.
SKYLOOP,VSN=P02104.
SKYLOOP,VSN=P01885.
SKYLOOP,VSN=P01902.
SKYLOOP,VSN=P01871.
SKYLOOP,VSN=P01810.
SKYLOOP,VSN=P01000.
EXIT.
DAYFILE.
/EOR
.PROC,SKYLOOP*I,VSN=(*F).
LABEL,TAPE1,F=S,LB=KU,PO=NR,NT,D=PE,#VSN=VSN.
SKYC.
REWIND,INPUT.
UNLOAD,TAPE1.
PFILM.
REVERT.
```

SKYC is the executable absolute binary file produced in compiling SKY, the NOS-to-VMS conversion code.

The file IN, which is read from memory, contains a single 0. This input to the code instructs it to process both energy channels in the data.

A product of this program is a plot file containing four frames.

1.) skymap in which a dot indicates data in the coordinate box. This gives you information concerning the sky coverage during the epoch plotted.

2.) skymap in which a dot represents a single observation of greater than 40 counts/second. This plot is not too useful, as it contains many spurious points.

3.) skymap similar to the first, with the difference being that a background subtracted threshold of 1.6 counts/second must be observed in order for a dot to appear on the plot.

4.) skymap of 3 second averages (reduces the number of spurious points included) of count rate greater than 40 counts/second.

These are plotted on microfiche by the PFILM command at the end of a successful processing of each input tape.

A 672 integer word array (60 bits each) was filled with the first byte (8 bits) of each reversed in order so that the VAX will read it correctly. The information associated with each 1 second observation contains 448 bits. Ninety of these were to be written into a given array (recall that a NOS word is 60 bits), so

Integer Array Size = 90 * 448 / 60 = 672 words.

To find a maximum record length, an integer fraction of 60 must be used to multiply by 448. Ten arrays per record was the chosen value, which gave an acceptably low value for MRL.

MRL = 10 * (90/60) * 448 = 15 * 448 = 6720 words.

APPENDIX B
COEFFICIENT VARIANCE/COVARIANCE DERIVATION

The decision to save only the variances of the background fit coefficients, and not the covariances also, was arrived at by the following logic. The variance of the fit to the equation for our background, Chapter II– Equation (1), can be expressed as

$$\begin{aligned}\sigma_y^2 &= (\mathrm{cos}\omega \mathrm{t})^2\sigma_{\mathrm{a}}^2 + (\mathrm{sin}\omega \mathrm{t})^2\sigma_{\mathrm{b}}^2 + \sigma_{\mathrm{c}}^2 \\ &\quad + 2\mathrm{cos}\omega t\ \sigma_{\mathrm{ac}}^2 + 2\mathrm{sin}\omega t\ \sigma_{\mathrm{bc}}^2 + 2\mathrm{sin}\omega t * \mathrm{cos}\omega t\ \sigma_{\mathrm{ab}}^2 \end{aligned} \tag{1}$$

The problem, then, is to derive expressions for the coefficient variances and covariances found in Equation (1).

In regression analysis,

$$\mathrm{S} \equiv \sum_{\mathrm{i}} [\mathrm{y_i} - \mathrm{a(t_i)cos}\omega \mathrm{t_i} - \mathrm{b(t_i)sin}\omega \mathrm{t_i} - \mathrm{c(t_i)}]^2$$

By setting $\partial\mathrm{S}/\partial\mathrm{a} = \partial\mathrm{S}/\partial\mathrm{b} = \partial\mathrm{S}/\partial\mathrm{c} = 0$, the minimum of the squares of the derivations, i.e., best fit, is found. First, define $\mathrm{x_i} = \mathrm{cos}\omega\mathrm{t_i}$ and $\mathrm{z_i} = \mathrm{sin}\omega\mathrm{t_i}$. Then, the simultaneous equations to be solved are

$$\mathrm{c}\sum_{\mathrm{i}} \frac{1}{\sigma_{\mathrm{i}}^2} = \sum_{\mathrm{i}} \frac{\mathrm{y_i}}{\sigma_{\mathrm{i}}^2} - \mathrm{a}\sum_{\mathrm{i}} \frac{\mathrm{x_i}}{\sigma_{\mathrm{i}}^2} - \mathrm{b}\sum_{\mathrm{i}} \frac{\mathrm{z_i}}{\sigma_{\mathrm{i}}^2} \tag{2}$$

$$\mathrm{c}\sum_{\mathrm{i}} \frac{\mathrm{x_i}}{\sigma_{\mathrm{i}}^2} = \sum_{\mathrm{i}} \frac{\mathrm{y_i x_i}}{\sigma_{\mathrm{i}}^2} - \mathrm{a}\sum_{\mathrm{i}} \frac{(\mathrm{x_i})^2}{\sigma_{\mathrm{i}}^2} - \mathrm{b}\sum_{\mathrm{i}} \frac{\mathrm{x_i z_i}}{\sigma_{\mathrm{i}}^2} \tag{3}$$

$$c\sum_i \frac{z_i}{\sigma_i^2} = \sum_i \frac{y_i z_i}{\sigma_i^2} - a\sum_i \frac{x_i z_i}{\sigma_i^2} - b\sum_i \frac{(z_i)^2}{\sigma_i^2} \tag{4}$$

To aid in the derivation, the following definitions are made

$$S = \left(\sum \frac{x_i}{\sigma_i^2}\right)^2 - \sum \frac{1}{\sigma_i^2} \sum \frac{(x_i)^2}{\sigma_i^2}$$
$$T = \left(\sum \frac{z_i}{\sigma_i^2}\right)^2 - \sum \frac{1}{\sigma_i^2} \sum \frac{(z_i)^2}{\sigma_i^2}$$
$$U = \sum \frac{x_i}{\sigma_i^2} \sum \frac{z_i}{\sigma_i^2} - \sum \frac{1}{\sigma_i^2} \sum \frac{x_i z_i}{\sigma_i^2}$$

where all summations are over i. Note S, T, and U are independent of y. By definition

$$\sigma_x^2 = \sum_i \sigma_i^2 \left(\frac{\partial x}{\partial y_i}\right)^2$$

where, in the current problem, x = a,b,c. It is found that

$$\sigma_b^2 = \frac{1}{U^2 - ST} \sum_i \frac{1}{\sigma_i^2} S$$

$$\sigma_a^2 = \frac{1}{U^2 - ST} \sum_i \frac{1}{\sigma_i^2} T$$

The solution for c is a little more complex, however the same procedure as used for a and b will lead to

$$\sigma_c^2 = \frac{1}{U^2 - ST} \sum_i \frac{1}{\sigma_i^2} (\left(\sum_i \frac{x_i z_i}{\sigma_i^2}\right)^2 - \sum_i \frac{(x_i)^2}{\sigma_i^2} \sum_i \frac{(z_i)^2}{\sigma_i^2})$$

Covariance, by definition, is

$$\sigma_{ij}^2 = \sum_k \sigma_k^2 \left(\frac{\partial_i}{\partial y_k}\right)\left(\frac{\partial_j}{\partial y_k}\right)$$

Using the appropriate equations from above, the covariances for the current problem are found to be

$$\sigma_{ab}^2 = \frac{1}{U^2 - ST}\sum_i \frac{1}{\sigma_i^2}(-U)$$

$$\sigma_{bc}^2 = \frac{1}{U^2 - ST}\left(U\sum_i \frac{x_i}{\sigma_i^2} - S\sum_i \frac{z_i}{\sigma_i^2}\right)$$

$$\sigma_{ac}^2 = \frac{1}{U^2 - ST}\left(U\sum_i \frac{z_i}{\sigma_i^2} - T\sum_i \frac{x_i}{\sigma_i^2}\right)$$

Tests were run to look at the relative magnitudes of the six terms in Equation (1). The total variance was always dominated by either the first or second term, depending on the value of ωt. The sum of the three variance terms dominated the sum of the covariance terms, with a maximum error of less than 20%. This proved to be acceptable for our purposes. In the VAX analysis program described in Chapter II–Section 3, the total variance of the background fit contributes less than 10% to the total variance of the point (sum of variance due to collimator response removal + variance due to background fitting). Therefore, the covariance terms were not kept in the new datastream.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

James R. Ipser, Chairman
Professor of Physics

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